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INDIA METEOROLOGICAL DEPARTMENT

SCIENTIFIC NOTES

Vol. VIII, No. 83.

On the forecasting of rain over South Bengal during the nor'wester season, mid-March to mid-May

By

A. K. ROY.

(Received on 19th October 1938.)

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On the forecasting of rain over south Bengal during the nor'wester season, mid-March to mid-May

BY

A. K. ROY.

(*Received on 19th October 1938.*)

Summary.—An empirical method of day-to-day forecasting of thunderstorm rain in south Bengal during the period, mid-March to mid-May, based on barometric pressures at 0800 hrs. local time at three stations in south Bengal is suggested. An examination of the data for 6 years, 1929 to 1934, shows that on days on which pressures at Barisal and Berhampur were both higher than the pressure at Calcutta, rain occurred in south Bengal on about 83 per cent. occasions. Further, when Berhampur pressure minus Calcutta pressure was + ·03″ or more, with Barisal registering higher pressure than Calcutta, rainfall occurred in south Bengal on 97 per cent. occasions.

Rainfall in south Bengal during the period, mid-March to mid-May, is usually associated with thunderstorms, which are commonly known as nor'westers. According to Sohoni*, the most important types of weather associated with nor'wester days in Bengal are, (*a*) the western disturbance type, (*b*) the east-west pressure-gradient over Bengal type and (*c*) the temperature contrast type. It is, however, evident that, for the occurrence of nor'westers of any of the above types in Bengal, the condition (*b*), *viz.*, the east-west gradient has to be satisfied in almost all cases, for, in the absence of such a gradient, an inflow of fresh maritime air into Bengal cannot take place, and no more than occasional and localised rainfall can be expected under such conditions. Out of 120 occasions during the six years 1929 to 1934, when three or more out of the 15 stations in south Bengal had rain, Barisal pressure minus Calcutta pressure was positive in 111 cases, zero in 7 cases and negative in the remaining 2.

An analysis of the day-to-day difference between atmospheric pressure (reduced to sea level) at Barisal and Calcutta at 0800 hrs. local time during the period mid-March to mid-May in the six years 1929-1934 shows that on 283 mornings during the period under consideration pressure at Barisal was higher than that at Calcutta; on 167 of these days, *i.e.*, on 59 per cent. occasions 1 or more of the 15*†stations in south Bengal had rainfall of 10 cents or more. On 77 mornings, pressure at Barisal was either equal to or lower than that at Calcutta, and on 23 of these days, *i.e.*, in 30 per cent. cases only, was there rainfall at one or more of the above 15 stations in south Bengal. If, however, we consider as rainy days only those days on which at least 3 out of the 15 stations had rain, it is seen that such rainfall occurred on 120 days in all during the 6 years 1929-1934. As has been mentioned already, out of these 120 days, Barisal pressure minus Calcutta pressure was positive on 111 mornings, zero on 7 and negative on the 2 remaining days. It is thus seen that the majority of the rainy days in south Bengal (rain at 3 or more stations being taken as the criterion for rainy days) is associated with higher pressure at Barisal than at Calcutta or, in other words, with a pressure gradient from east to west. It should, however, be noted that although such a gradient was present on 283 mornings during the six years under consideration, only 111, *i.e.*, 39 per cent. of these days turned out to be rainy. It is therefore clear that although higher pressure at Barisal than at Calcutta is an important condition for raininess in south Bengal, this criterion alone does not provide a satisfactory clue for the forecasting of weather in south Bengal, for, if rain is predicted on all the days when the above condition is satisfied, forecasts may fail on about 61 per cent. of the occasions. An attempt was therefore made to find out some other factor which would enable a more successful prediction of rainfall in south Bengal during the period mid-March to mid-May.

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*The Journal and Proceedings, Asiatic Society of Bengal, Vol. XXVIII, 1932, No. 1. (pp. 349—357).

With this object in view, day-to-day differences of atmospheric pressure at 0800 hrs. at Berhampur and Calcutta were also tabulated. A sample of tables showing the type of information obtained on the basis of (*a*) Barisal—Calcutta and (*b*) Berhampur—Calcutta pressure differences, in relation to rainfall during next 24 hours, is given in the Appendix. The results obtained from an analysis of six years' data are summarised as in the *table* below.—

——————	Class I Barisal > Calcutta Berhampur > Calcutta.		Class II Bari. > Cal. Ber. $\ngtr$ Cal.	Class III Bari. = Cal.	Class IV Bari. < Cal.
	(*a*) Ber.—Cal. = + ·03″ or more.	(*b*) Ber.—Cal. = + ·02″ or + ·01.″			
Total No. of days	31	71	181	37	40
No. of days on which at least one station in south Bengal had rain	30	55	82	14	9
Percentage of days ..	97%	77%	45%	38%	22%
No. of days on which 3 stations or more had rain ..	25	34	52	7	2
Percentage of days	81%	48%	29%	19%	5%
Average rainfall (total of all the 15 stations in south Bengal) per day on which rain fell at one or more stations	5·6″	2·5″	2·2″	1·4″	0·7″
Average No. of stations that had rain on a rainy day defined as above	7·2	4·3	3·9	3·0	1·5

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* †For the purpose of this study, only 15 stations, *viz.*, Faridpur, Barisal, Comilla, Noakhali, Asansol, Bankura, Krishnagar, Burdwan, Midnapore, Calcutta, Saugor Island, Satkhira, Khulna, Narayanganj and Jessore below the latitude of Berhampur out of the 17 stations in south Bengal, the data for which are printed in the Calcutta Daily Weather Report have been taken into account. The two remaining stations, *viz.*, Chittagong and Cox's Bazar in the extreme southeast of Bengal which, from the meteorological point of view, come more appropriately under the group of stations in the Arakan coast have been excluded.

The table above is self-explanatory and shows that conditions are most favourable for rainfall in south Bengal when morning pressures at both Barisal and Berhampore are higher than the pressure at Calcutta, *i.e.*, on days coming under class I, and further that the chances of rain are greater, the greater the positive difference between the pressures at Berhampur and Calcutta. It is also seen that the average rainfall per rainy day is greater and the distribution of rainfall more widespread on days coming under class I than on days of other classes, and that, on the average, the maximum amount of rainfall with the most widespread distribution occurs on days of class I (*a*), *i.e.*, on days when pressure at Berhampur in the morning is higher than that at Calcutta by ·03″ or more. The chances of 3 or more stations in south Bengal getting rain during the season decrease progressively as we pass on from class I (*a*) to the other four classes. On days coming under classes III and IV such rainfall is restricted to only 19 and 5 per cent. cases respectively.

It is seen from the above analysis that the most favourable conditions for rainfall in south Bengal are

(1) higher pressure at Barisal than at Calcutta *i.e.*, an east-west pressure gradient, which helps an inflow of fresh maritime air into Bengal from some southerly direction

and

(2) higher pressure at Berhampur than at Calcutta, a condition which indicates the probable presence of dry and perhaps somewhat cooler land air to the north of deltaic Bengal at some upper level, if not actually on the ground level, and perhaps also its movement towards deltaic Bengal.

In cases when condition (1) alone is satisfied, the warm moist air from the south merely sweeps over the plains of Bengal but, except under conditions of marked superadiabatic lapse rate, caused by strong insolation, the moist air fails to rise appreciably until it reaches north Bengal or Assam and strikes the Himalayas. Rainfall, if any, on such days is, therefore, likely to be restricted generally to north Bengal and Assam, south Bengal as a rule, getting very little rain. This is also confirmed in a general way by an examination of the data for a few years. The condition (2) helps the setting up of a barrier in the path of the warm moist air flowing over south Bengal and thereby its ascent and eventual precipitation in the form of cloud and rain.

In the light of the results brought out in the above table, it is considered that a convention as suggested below may, with advantage, be adopted as an auxiliary to the synoptic map for prediction of thunderstorm rain in south Bengal during the period mid-March to mid-May.

(1) On days coming under class I (*a*), forecasts for south Bengal may read, " Fairly widespread thunderstorm with locally heavy rain will occur in south Bengal."

(2) On days coming under class I (*b*), we may say " Thunderstorms and local rain likely in south Bengal."

(3) On days coming under class II, forecast may read " There is a chance of a few thundershowers in south Bengal ", provided the synoptic charts otherwise support such a conclusion.

(4) On days coming under class III, we may say " There is a slight chance of scattered thundershowers ", only when the synoptic charts show that conditions otherwise are distinctly favourable.

(5) On days coming under class IV, rain and thunderstorms in south Bengal should not, as a rule, be predicted, unless there is a depression or storm in the neighbourhood or the synoptic charts reveal some well-marked conditions which are distinctly favourable for rainfall.

APPENDIX.

Pressure differences in inches (at 0800 hrs. local time) between Barisal and Calcutta and between Berhampur and Calcutta, and rainfall (during 24 hours ending at 0800 hrs. L. M. T. the next day) at fifteen stations in south Bengal during the period 16th March to 15th May, 1933.

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List of stations with their abbreviations.

Calcutta ..	.. CAL	Khulna ..	.. KHL	Asansol ..	.. **ASL**
Midnapore	.. MDP	Barisal ..	.. BSL	Noakhali	.. **NKH**
Burdwan ..	.. BDWN	Jessore ..	.. JSR	Comilla ..	.. CML
Bankura	.. BNK	Narayanganj	.. NGJ	Krishnagar	.. KRG
Satkhira ..	.. STR	Faridpur	.. FRD	Saugor Island	.. SGR.I.

Date.	Pressure difference in inches at 0800 hrs.		Stations at which rainfall of 0·1″ or more was recorded during the following 24 hrs., with the amount of rainfall shown against them.
	Barisal ***minus*** Calcutta.	Berhampur ***minus*** Calcutta.	
March (1933).			
16	−·01	+·01	
17	+·02	00	
18	+·03	+·02	
19	+·02	+·01	
20	+·03	−·02	
21	+·02	00	BNK (0·1).
22	−·01	00	CML (0·1) ; KRG (0·1).
23	+·01	+·02	NKH (0·5).
24	00	−·01	
25	+·03	00	NGJ (0·1) ; KRG (0·2).
26	00	−·01	MDP (0·2).
27	+·01	+·01	BSL (0·7) ; CML (0·3) ; NKH (0·1) ; STR (0·3) ; KHL (0·1).
28	+·02	−·01	
29	+·02	00	
30	−·01	−·01	
31	+·01	00	
April (1933).			
1	00	−·01	
2	+·01	−·01	
3	00	−·02	
4	+·02	−·02	
5	+·04	−·02	

Date.	Pressure difference in inches at 0800 hrs.		Stations at which rainfall of 0·1″ or more was recorded during the following 24 hrs., with the amount of rainfall shown against them
	Barisal *minus* Calcutta.	Berhampur *minus* Calcutta.	
April (1933).			
6	+·02	—·04	
7	+·04	—·02	
8	+·02	00	
9	—·01	—·02	
10	+·01	—·02	
11	+·04	—·01	BNK (1·8); BDWN (·03); MDP (0·2); CAL (0·1); NGJ (0·3); KGR (0·8).
12	+·02	+·01	BNK (0·1); MDP (0·1); STR (0·1); KHL (0·3); JSR (0·3).
13	+·05	+·03	BSL (2·1); BNK (0·9); BDWN (3·0); MDP (0·6); SGR. I (0·7); CAL (0·8); KHL (1·8); JSR (4·7).
14	+·01	+·03	FRD (1·1); BSL (0·3); CML (0·5); NKH (2·0); BNK (0·2); BDWN (0·1); SGR. I (0·5); CAL (1·1); NGJ (0·5); STR (0·3); KHL (0·5); JSR (1·4); KGR (0·4).
15	+0·4	00	FRD (1·3); BNK (0·2); BDWN (0·1); JSR (1·1); NGJ (0·4); KGR (1·1).
16	+·02	+·05	FRD (1·0); BSL (1·5); CML (1·3); NKH (1·1); MDP (0·6); SGR. I(1·1); CAL (0·5); STR (1·2); KHL (3·6); NGJ (2·2); JSR (0·9); KGR (0·4).
17	00	+·01	
18	+·01	—·02	NGJ (0·4).
19	+·03	—·01	NGJ (0·2).
20	+·04	+·01	
21	+·05	+·01	
22	+·06	—·01	FRD (2·2); BSL (0·1); BNK (0·3); BDWN (0·1); SGR. I (0·2); CAL (0·2); KHL (1·6); JSR (1·0); KGR (1·7); NGJ (1·9); STR (0·4).
23	00	+·05	CAL (0·3); STR (0·1); JSR (0·2); KGR (0·5);
24	—·01	—·02	MDP (0·1).
25	00	00	
26	+·01	—·01	
27	+·02	00	
28	+·02	00	

Date.	Pressure difference in inches at 0800 hrs.		Stations at which rainfall of 0·1″ or more was recorded during the following 24 hrs., with the amount of rainfall shown against them.
	Barisal *minus* Calcutta.	Berhampur *minus* Calcutta.	
29	+·05	+·01	FRD (0·8); BSL (0·4); CML (0·1); STR (0·2); KHL (0·1); JSR (0·5); NGJ (0·4).
30	+·02	+·03	FRD (0·6); BSL (0·6); CML (0·7); NKH (0·1); BNK (0·1); BDWN (0·9); SGR. I (0·1); STR (0·4); NGJ (0·5); KHL (0·1); KGR (5·6).
May (**1933**).			
1	—·01	+·02	MDP (0·1).
2	+·01	+·02	BDWN (0·4); CAL (0·6); KGR (0·4).
3	—·01	00	
4	00	00	FRD (0·1); BNK (0·8); BDWN (0·2); STR (0·1); NGJ (0·1).
5	+·01	+·01	FRD (1·2); BSL (0·1); BNK (0·7); BDWN (0·3); CAL (0·7); STR (0·7); KHL (0·3); JSR (1·0); NGJ (0·5); KGR (0·3).
6	+·03	+·04	BSL (2·1); NKH (0·2); MDP (0·9); SGR. I. (0·6); STR (0·3); KHL (0·4).
7	+·01	+·01	FRD (0·1); BSL (1·4); CML (1·2); NKH (0·3); MDP (0·2); CAL (0·7); STR (0·9); KHL (2·8); JSR (0·5); KGR (2·1).
8	+·02	+·04	FRD (1·0); BSL (0·2); CML (0·1); BNK (0·8); BDWN (4·0); MDP (0·2); SGR. I (1·1); CAL (2·6); NGJ (0·3); KHL (1·5); JSR (1·6); KGR (0·8).
9	+·03	+·02	BSL (0·3); BNK (0·1); SGR. I (0·1); KHL (1·4).
10	+·01	+·02	FRD (0·5); BSL (1·9); CML (0·2); NKH (2·3); SGR. I (0·4); JSR (0·3); NGJ (1·3).
11	+·04	+·04	FRD (0·6); SGR. I (0·1); CAL (0·4); STR (0·1); KHL (0·3); NGJ (0·7).
12	00	+·03	BDWN (0·6); MDP (0·3); CAL (0·1); KHL (0·3); JSR (0·1).
13	+·01	+·01	
14	+·02	+·01	BSL (0·1); BDWN (0·5); MDP (0·5); CAL (0·1); SGR. I (0·8); STR (1·6); BNK (0·1); KGR (0·2).
15	—·02	—·01	

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A Statistical Analysis of the monthly rainfalls in the Amraoti District (Berar)

BY

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A STATISTICAL ANALYSIS OF THE MONTHLY RAINFALLS IN THE AMRAOTI DISTRICT (BERAR)*

BY

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Abstract. The monthly rainfall data of 12 rain-gauge stations (for June—September) in the Amraoti district for a period of 41 years 1894—1934 are studied with a view to find whether the district is homogeneous with respect to rainfall. The analysis of variance indicates the relative importance of the variation between locations and variations from year to year. Exclusion of one station (Chikalda) which has on an average double the rainfall of other stations from the analysis of variance reduces the variance due to location considerably, but still the variance due to location is significant. The homogeneity of the whole tract regarding seasonal variations is indicated by the high correlation coefficients among the rainfall amounts at various stations in all the four months.

Introduction.—A knowledge of the variability in time and space of a meteorological factor like rainfall is of importance in meteorological practice. In controlling the general distribution and density of meteorological stations over the country one would naturally attempt to divide the country into divisions or zones within each of which the average values as well as the variabilities of the meteorological factors are more or less similar. Such a division of the country into small areas, each with some homogeneity in its climatic elements, is also of great help to the weather forecaster in determining the ultimate units of area for which a particular forecast would hold. Similarly, in long-range or seasonal forecasts also, one would like to deal with geographical units each of which is homogeneous climatically.

The question naturally arises how we would test the homogeneity or otherwise of an area with regard to climate if we are given the data of, say, p meteorological stations over that area, extending over a series of n years. The data may be tabulated as follows :—

Year.	Station A	Station B	..	Station P	Mean.
1	a^1	b_1	..	p_1	x
2	a	b_2	..	p_2	x
3	a^3	b_3	..	p_3	x^3
.	.	.	..	.	.
.	.	.	..	.	.
.	.	.	..	.	.
n	a_n	b^n	..	p_n	x_n
Mean	a	b	..	p	x

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*The present investigation was made in the Agricultural Meteorology Section (India Meteorological Department) financed by the Imperial Council of Agricultural Research.

Here A, B, ... P are the p meteorological stations, $a_1, a_2, a_3 \ldots\ldots a_n$ in the second column representing the series of data (of a particular element) of station A for n years, a being the mean value. In the first row $a_1, b_1 \ldots\ldots p_1$ represent the values of the first year at the various stations and x_1 is the mean value for the first year for the area represented by the stations ; x is the mean value of the entire series of data of p stations for n years.

The variation among the data given in the above table is due to :

(1) variation of locality,

(2) variation between years, and

(3) variation due to chance or error.

The analysis of variance will be as shown in the table given below :—

Source of Variation.	Sum of Squares.	Degrees of Freedom	Variance.
1. Between stations.	$n\sum_{a}^{p}(a-x)^2$	$p-1$	$V_1 = \dfrac{n\sum_{a}^{p}(a-x)^2}{p-1}$
2. Between years.	$p\sum_{x_1}^{x_n}(x_1-x)^2$	$n-1$	$V_2 = \dfrac{p\sum_{x_1}^{x_n}(x_1-x)^2}{n-1}$
3. Error.	$\sum_{a}^{p}\sum_{r=1}^{rn}(a_r-x)^2 - n\sum_{a}^{p}(a-x)^2 - p\sum_{x_1}^{x_n}(x_1-x)^2$	$(n-1)(p-1)$	$V_e = \dfrac{\text{sum of squares due to error}}{(n-1)(p-1)}$
Total.	$\sum_{a}^{p}\sum_{r=1}^{rn}(a_r-x)^2$	$np-1$	

If there are no variations of climate from station to station or from year to year, then, V_1 and V_2 will be of the same order of magnitude as V_e, *i.e.*, all variations will tend to be random. When there are real variations between stations and between years, V_1 and V_2 will be significantly larger than V_e. The values of $\frac{V}{V_e}$ which are above the conventional levels of significance for various degrees of freedom of the two variances are given by Fisher and Yates (*2, Table V*). For a more detailed discussion of the method of analysis of variance a reference may be made to Fisher (1) and Irwin (4).

Statistical analysis of the monthly rainfalls in the Amraoti District (Berar).— In the case of rainfall it is usual to take the arithmetic mean of readings at several stations in an area* as representing the average rainfall in that area. Such an average is likely to give a false estimate of the rainfall when the area is very large or when it contains stations getting widely varying rainfall amounts. Weighting by areas may, to a certain extent, reduce the error, but involves some arbitrariness in the assignment of the area appropriate to each rain-gauge.

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*The grouping of stations is usually according to the administrative units like districts, taluks, etc.

In this section we shall apply the method indicated in the introductory part to an examination of the variability of rainfall in the Amraoti district in Berar. The data consist of the monthly values of rainfall recorded at the rain-gauge stations in the district over a period of 41 years, 1894 to 1934. The district can be divided broadly into two parts, (1) an expanse of level country lying in the rich valley of Payanghat and (2) a tract of mountainous country of little agricultural value. The first part (*see map*) consists of five taluks, Amraoti, Daryapur, Ellichpur, Morsi and Chandur, with eleven rain-gauge stations in all, Amraoti having three and the others having two each. The second part consists of one taluk called Melaghat which contains two rain-gauge stations, Chikalda and Dharni. Dharni was started only about 1901 and hence the data for the full period is not available for this station. Hence only Chikalda rainfall has been considered from this taluk.

Table 1 gives the list of rain-gauge stations in each Taluk and the area of each Taluk. The rainfall of each month of the four rainy months, June, July, August and September over a period of 41 years commencing from 1894 is studied here. The mean monthly rainfalls with the standard deviations are shown in *Table 1.*

It is seen from this table that the mean rainfall at Chikalda is considerably more than at plain stations in all the months considered. This suggests that the Melaghat tract is quite different from the plains so far as rainfall is concerned. The average rainfalls over the district including Chikalda and excluding it are also given to indicate the effect of this station on the average for the area. The rainfall data for each of the 12 rain-gauge stations extend over 41 years giving $12 \times 41 - 1 = 491$ degrees of freedom for the set of figures for each month. The total sum of squares for each month can be partitioned into three parts as follows :—

(1) between stations or locations (11 degrees of freedom),

(2) between years (40 degrees of freedom),

(3) Residual (440 degrees of freedom).

The analysis of variance for each month is given in *Table 2 (a).*

The variances between stations for all the months are significantly different from the residual variances as shown below. The range of values of variance ratios given in Fisher and Yates (*2, Table V*) does not include the combination $n_1 = 11$ and $n_2 = 440$, and so the differences in variances have been tested by the Z-test (*Fisher 1, p. 237, Section 41*).

$Z = \frac{1}{2}\log_e \frac{V_1}{V_2}$		5% and 1% values of Z.
June	1·1029	5% value = 0·2941.
July	1·9566	
August	2·1678	1% value = 0·4048
September	1·5858	

This shows that the variation between stations of rainfall amounts in all months exceeds considerably the variation that can be expected by mere chance. We have already seen from *Table 1* that the station Chikalda has a considerably heavier rainfall than the other stations and so it may be interesting to know how much of the variations between stations is accounted for by that one station. So the analysis of variance for the rainfall of 11 plain stations in the district excluding Chikalda has been calculated and is given in *Table 2 (b)*. The allocation of degrees of freedom for this table is:

between stations	10
between years	40
Residual	400
Total ..	450

It may be noted that the variance due to locations has diminished considerably in all months due to the exclusion of the station Chikalda, showing that the heterogeneity among the stations indicated by the variance due to locations in *Table 2 (a)* is due to the inclusion of Chikalda in the group of rain-gauge stations.

Coming to *Table 2 (b)* we may again test how the reduced variances between stations compare with the residual or error variation.

$Z = \frac{1}{2} \log_e \frac{V_1}{V_e}$	.. .. ..	5% and 1% values of Z.
June 0·6135	.. .. ..	
July 0·6339	.. .. ..	5% value = 0·3058
August 0·9540	.. .. ..	
September 0·4079	.. .. ..	1% value = 0·4203

The above results show that still the variance due to locations is significantly higher than what may be expected due to chance variations. From *Table 1*, column 11 it can be seen that out of the 11 stations, Barur and Talegaon have on the whole a higher rainfall though the differences are much smaller than in the case of Chikalda. The variances between stations considering only 9 stations (excluding Barur and Talegaon) have been determined and are included in the following Table.

Table of variance between stations.

	12 Stations.	11 Stations.	9 Stations.
June	27·3	9·8	5·6
July	350·8	19·0	2·4
August	420·9	26·5	10·8
September.. ..	130·2	8·8	6·8

While the exclusion of Chikalda from the group of stations has effected a considerable reduction in the variance between stations for all the months, exclusion of two stations, Barur and Talegaon which showed slightly higher rainfall than the rest does not lead to a substantial reduction except for the month of July. An explanation of the fact that the variance due to locations is still significantly greater than the residual variation may lie in the inadequacy of the number of locations available in the tract.

The variances "between years" in *Tables 2 (a)* and *2 (b)* are all very high showing thereby that a large part of the total variability of rainfall is controlled by the seasonal fluctuations.

The high values obtained for variances "between years" in *Tables 2* (*a*) and *2* (*b*) suggest that if seasons do affect the stations inside the district similarly then this effect should be indicated by high regression amongst the rainfall amounts recorded at the various rain-gauge stations in the area. *Table 3* (*a*) shows the correlation coefficients of rainfall at Amraoti with the rainfall at the other 11 stations (including Chikalda) in the district for each of the four months. It is interesting to note that Chikalda, in spite of its higher average rainfall, shows the same order of regression with Amraoti as other stations in the district. This indicates that though Chikalda gets a higher amount of rainfall, its seasonal variations are not independent of the general seasonal variations in the whole district. In *Table 3* (*b*) the five taluk headquarter stations (excluding Chikalda) have been chosen and all the inter-correlation coefficients among them are given. Lastly, in *Table 3* (*c*) the correlation coefficients between rainfalls at the stations in the same taluk are given. For testing the significance of all these correlation coefficients the 5 per cent. value of correlation coefficient according to Fisher (^{2}) is 0·31. But for each month 21 correlation coefficients have been found (excluding the correlation coefficient of Chikalda with Amraoti) and so the 5 per cent. level of significance is 0·55 using Walker's criterion as extended by Savur and Gopal Rao (^{3}). Applying the latter test it is found that all the correlation coefficients in *Tables 3* (*a*) to *3* (*c*) are significant except those for Amraoti with Chandur Bazar, Morsi and Barur for July and that for Daryapur and Morsi in June. A comparison of *Tables 3* (*b*) and *3* (*c*) indicates that probably the rainfall at stations within the same taluk is correlated to a greater extent than rainfall between stations in different taluks.

Conclusions.—The analysis of variance of the monthly rainfall data for the four months for the rain-gauge stations in Amraoti district shows the relative importance of the variation between locations and variations from year to year. Exclusion of one station (Chikalda) which has on an average double the rainfall of other stations from the analysis of variance reduces the variance due to locations considerably, though still the variance due to location is significant. The homogeneity of the whole tract regarding seasonal variations is indicated by a study of correlation coefficients among the rainfall amounts at various stations for all the four months. In this investigation the distribution of rainfall in the Amraoti district in each of the months considered has been assumed not to depart significantly from the normal distribution.

In conclusion the author wishes to express his grateful thanks to Dr. L. A. Ramdas, for suggesting the problem, and to Dr. R. J. Kalamkar and Mr. V. Satakopan for help in the discussion of some of the points discussed in the paper.

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TABLE 1.

Name of Taluk and areas in square miles.	Name of Station.	Mean Monthly rainfall and Standard Deviation.								Total. (June—Sept.)
		June.		July.		August.		September.		
		Mean.	S.D.	Mean.	S.D.	Mean.	S.D.	Mean.	S.D.	
1	2	3	4	5	6	7	8	9	10	11
Amraoti (672) ..	Amraoti ..	5·98	3·12	8·44	3·99	6·40	3·69	5·88	3·66	26·72
	Kholapur ..	5 65	2·95	8·81	4·53	5·78	3·17	5·86	3·78	26·10
	Badnera ..	6·05	3·36	8·64	3·84	6·08	3·55	5·67	3·06	26·44
Daryapur (505) ..	Daryapur ..	4·91	2·51	8·69	3·62	5·21	2·84	5·21	3·36	24·02
	Anjangaon ..	5·26	2·93	8·10	3·16	5·83	3·21	5·30	3·40	24·47
Ellichpur (469) ..	Ellichpur ..	5·83	2·79	8·60	3·67	6·33	3·55	5·17	3·72	25·92
	Chandur Bazar ..	5·51	2·66	8·73	3·81	6·47	3·56	5·54	3·46	26·25
Morsi (622) ..	Morsi	5·73	3·14	8·31	2·63	6·97	3·36	5·57	3·64	26·58
	Barur	6·84	3·57	10·63	4·31	8·18	4·35	6·48	3·98	32·13
Chandur (855) ..	Chandur	5·91	3·40	8·81	4·52	6·46	4·02	6·45	4·41	27·51
	Talegaon ..	5·87	3·29	9·39	3·90	7·26	4·40	6·17	3·60	28·69
Melaghat (1631) ..	Chikalda ..	8·09	3·97	18·71	6·87	17·23	7·20	11·74	6·99	55·77
District Mean (excluding Chikalda) ..		5·77		8·83		6·45		5·75		26·80
District Mean (including Chikalda) ..		5·96		9·66		7·35		6·25		29·22
Percentage increase in the Mean ..		3·3%		9·4%		13·9%		8·7%		9·0%

TABLE 2 (*a*).

Table of Analysis of Variance—Amraoti District (12 Stations).

	Degrees of freedom.	June.		July.		August.		September.	
		Sum of squares.	Variance.	Sum of squares.	Variance.	Sum of squares.	Variance.	Sum of squares.	Variance.
Locations ..	11	299·79	27·25	3858·92	350·81	4629·31	420·85	1432·61	130·24
Years ..	40	3415·51	85·39	5386·66	134·67	5506·09	137·65	5821·05	145·53
Residual ..	440	1327·44	3·02	3115·48	7·08	2424·36	5·51	2403·50	5·46
Total ..	491	5042·74	10·27	12361·07	25·18	12559·77	25·58	9657·16	19·67

TABLE 2 (*b*).

Table of Analysis of Variance—Amraoti District (11 Stations).

	Degrees of freedom.	June.		July.		August.		September.	
		Sum of squares.	Variance.	Sum of squares.	Variance.	Sum of squares.	Variance.	Sum of squares.	Variance.
Locations ..	10	97·95	9·79	190·08	19·01	264·94	26·49	88·39	8·84
Years ..	40	2963·41	74·09	4477·00	111·93	4287·48	107·19	4707·21	117·68
Residual ..	400	1147·94	2·87	2138·87	5·35	1571·08	3·93	1565·84	3·91
Total ..	450	4209·30	9·35	6805·95	15·12	6123·50	13·61	6361·44	14·14

TABLE 3 (*a*).

Correlation Coefficients of rainfall at Amraoti and other rain-gauge stations.

	June.	July.	August.	September.
Kholapur	·75	·64	·82	·85
Badnera	·82	·93	·91	·88
Daryapur	·56	·66	·74	·85
Anjangaon	·67	·61	·78	·79
Ellichpur	·68	·63	·59	·87
Chandur Bazar	·69	·47	·67	·74
Morsi	·69	·48	·78	·76
Barur	·61	·48	·67	·63
Chandur	·87	·85	·81	·84
Talegaon	·73	·78	·84	·72
Chikalda	·73	·63	·70	·72

TABLE 3 (*b*).

Correlation Coefficients of rainfall amongst the taluk headquarter stations.

	June.				July.			
	Daryapur.	Ellichpur.	Morsi.	Chandur.	Daryapur.	Ellichpur.	Morsi.	Chandur.
Amraoti	·56	·68	·69	·87	·66	·63	·48	·85
Daryapur	..	·68	·54	·70	..	·57	·68	·72
Ellichpur	..	..	·67	·74	..	..	·66	·57
Morsi	..	..	..	·82	..	..	..	·58

	August.				September.			
	Daryapur.	Ellichpur.	Morsi.	Chandur.	Daryapur.	Ellichpur.	Morsi.	Chandur.
Amraoti	·74	·59	·78	·81	·85	·87	·76	·84
Daryapur	..	·61	·68	·70	..	·81	·69	·64
Ellichpur	..	..	·75	·49	..	..	·87	·68
Morsi	..	..	..	·70	..	..	..	·74

TABLE 3 (c).

Correlation Coefficients of rainfall between rain-gauge stations in the same Taluk.

	June.	July.	August.	September.
Amraoti—Badnera	·82	·93	·91	·88
Amraoti—Kholapur	·75	·64	·82	·85
Badnera—Kholapur	·78	·71	·82	·88
Daryapur—Anjangaon	·57	·70	·82	·88
Ellichpur—Chandur Bazar	·78	·78	·83	·87
Morsi—Barur	·71	·80	·76	·82
Chandur—Talegaon	·89	·83	·89	·96

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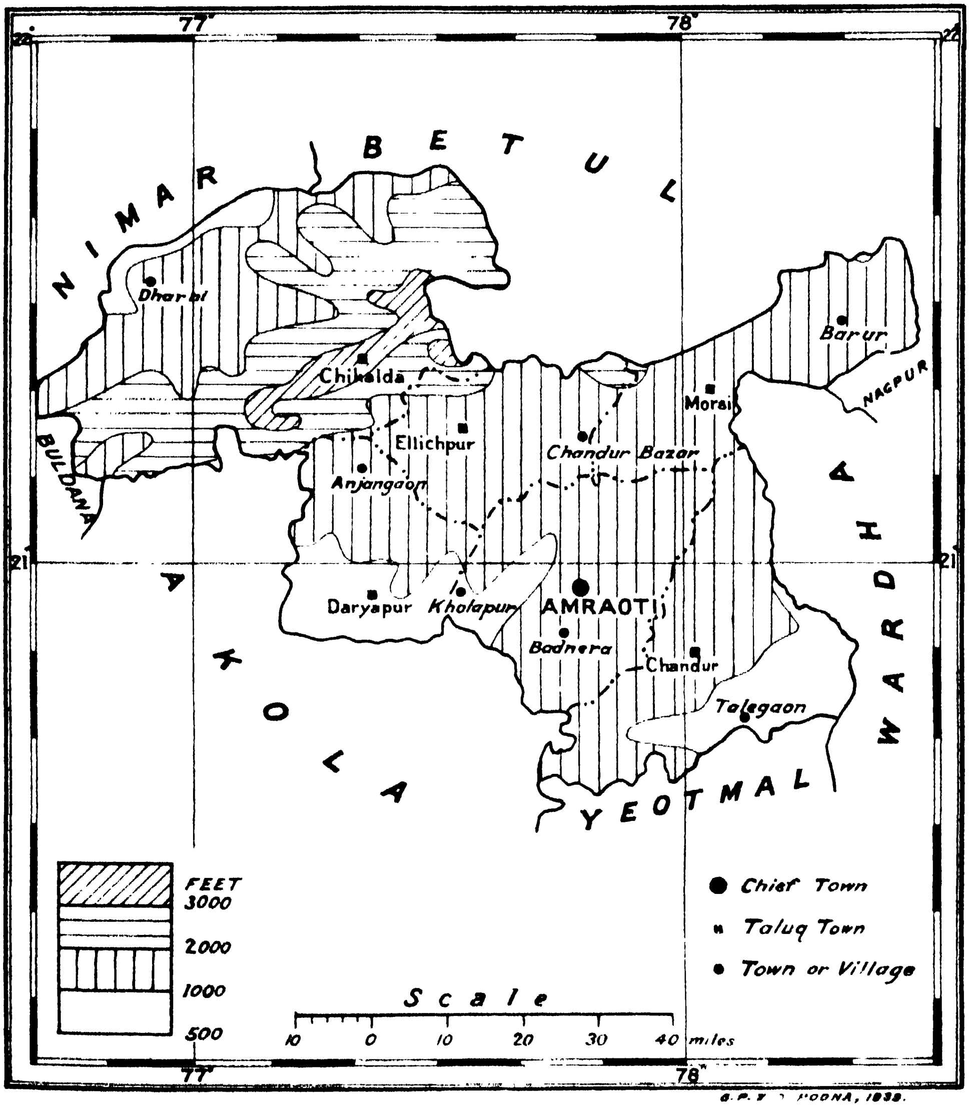
AMRAOTI DISTRICT



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A note on some measurements of cloud heights at Poona, Bombay and Madras.

BY

K. P. RAMAKRISHNAN.

Abstract.—In this paper, statistics of low cloud heights at Bombay and Poona during the southwest monsoon season and at Madras during the northeast monsoon season at different parts of the day are given in the form of frequency tables. The measurements were made either by ' ceiling ' or by ' pilot' balloons and extended over three or four years For Poona observations made at night by using a searchlight are also given. Some examples of short period fluctuations in cloud heights are also shown from these searchlight measurements.

An important item of climatological information along air routes is the height of base of low cloud and its diurnal variations. The mean, maximum and minimum values of the heights of each kind of cloud in different seasons for seven stations in India deduced mainly from the heights at which pilot balloons disappeared by entering cloud have been given in a paper by Narayanan and Manna*. The present note contains an analysis of some regular measurements made for this purpose at Bombay, Poona and Madras during the years 1932-38.

Day-time measurements.

The measurements during day consisted in noting the time at which a balloon —either pilot or ceiling—entered the cloud. The height of the balloon at that instant gives the height of base of cloud. In the case of pilot balloons, heights were measured by the tail method; with ceiling balloons, these were obtained by assuming a uniform rate of ascent (A) as calculated from the weight (W) and free lift (L) of the balloon by the formula :

$$A = 84 \frac{L^{\frac{1}{2}}}{(L+W)^{\frac{1}{3}}}$$

During the period 1932-35, Poona had one regular pilot balloon ascent a day at dawn, and Madras had two, one at dawn and the other at 14 or 15 hours. At Bombay, pilot balloon observations with one regular ascent per day (at dawn) started in

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*** M. V. Narayanan and M. P. Manna**: Heights of base of clouds in India as determined from pilot balloon ascents, Ind. Met. Dep. Sci. Notes, III, 25 (1931).

1933 ; the observations at Bombay in 1932 thus refer to ceiling balloon ascents only. The observations were more numerous at Poona than at the other two stations. The cloud heights obtained have been classified into four groups depending on the time of the day and expressed in the form of frequency tables for the internationally adopted height steps. (*Tables 1-3*).

It will be seen from the previous paragraph and *Tables 1-3* that the data for some hours of observation are based mostly on pilot balloon ascents while those for other hours are based mainly on ceiling balloon ascents. An important difference between the conditions under which these two sets of ascents are made should be borne in mind when trying to draw from these data inferences as to the diurnal variation of the height of cloud. In every pilot balloon ascent, the object being to measure winds to as high levels as possible, the observer waits for a chance for the clouds to rise within the margin of time allowed. In a ceiling balloon ascent, on the other hand, the object being to measure cloud height, the observer waits for a chance for the presence of low cloud within the time-margin. The former will therefore give greater frequency of occasions of clouds being either absent or occurring at greater heights than the latter. For obtaining unbiassed information of the diurnal variation of cloud heights at any station, therefore, it seems preferable to have ceiling balloon ascents always, irrespective of whether pilot balloon ascents are made or not, and to restrict the time limit to a small value, say 15 to 20 mins.

From 1st January 1937, frequencies of low cloud heights for each regular hour of pilot balloon ascent, including estimated values on days when the pilot balloon did not enter the cloud, are being given for all the above stations in the publication *Monthly Frequency Tables*.

Night-time measurements.

Of the 3 stations, regular measurements by means of searchlight were made at Poona only. Trials were first made in 1934 with a long base-line of about 1·1 km. Continuous observation at short intervals showed fluctuations of the height of cloud. The successive height-values obtained on 4 days in this year are given in *Fig. 1.* A great advantage of the searchlight method is that it is almost the only method by which such fluctuations over even moderate lengths of time can be followed. In 1935, observations were made on a larger number of days, with nearly the same base-line as in 1934. Later, for practical reasons, the base-line was shortened to about 240 metres ; and from 1937 onwards observations are being made every night, between 20 and 21 hrs. in the monsoon season. As it is rather difficult to take observations during rain, rainy weather has been missed on several occasions. On the other hand, if there were no cloud to start with, the observer waited for an opportunity for cloud. The combined results of measurements in the years 1935, 1937 and 1938 are given as frequency tables.

The heights given by individual observations on every night in the monsoons of 1937 and 1938 together with the mean cloud amount within the hour over which the observations were spread are plotted in *Fig. 2.* It is rather difficult to distinguish cloud types at night, and hence the cloud amounts generally refer to all kinds of cloud put together except that cloud amount is given as 0 (zero), whenever there was no low cloud, irrespective of whether medium or high cloud was present or not.

Fig. 2 shows all height-values obtained on one night along one vertical line and does not clearly bring out the variation with time. To bring out the variation with time, the height-values on a few typical nights are plotted against time in *Fig. 3.* It will be noticed that at some instants, clouds were observed simultaneously at two or three different levels. The lines drawn connecting the different points are only tentative.

TABLE 1.—*Summary of low cloud height measurements at Poona (1932-35).*

		Height of cloud in metres above ground.								No low cloud.	Height not determined due to other causes.	No. of observations.
		0-99.	100 to 199.	200 to 299.	300 to 599.	600 to 999.	1000 to 1499.	1500 to 1999.	2000 to 2499.			
JUNE.												
6 — 9 hrs. ..	..				1	11	5	1		7	32	57
10—12 hrs. ..	..			1	11	20	6				8	46
13—15 hrs. ..	..			1	5	18	9	4			9	46
15 hrs. to sunset	..			1	8	17	5	4	1		10	55
All hours ..	No.			3	25	66	25	9	1	7	68	204
	%			*1*	*13*	*33*	*13*	*5*	*1*	*3*	*34*	
JULY.												
6 — 9 hrs. ..	..				2	32	18	1	1	3	65	122
10—12 hrs. ..	..				19	52	15	1			12	99
13—15 hrs. ..	..				26	26	9	2			22	85
15 hrs. to sunset	..				15	39	20	2			29	105
All hours ..	No.				62	149	62	6	1	3	128	411
	%				*15*	*36*	*15*	*1*		*1*	*31*	
AUGUST.												
6 — 9 hrs. ..	..				6	50	19	2		6	43	126
10—12 hrs. ..	..				22	41	17		1		19	100
13—15 hrs. ..	..				11	28	15	3	2		24	83
15 hrs. to sunset	..				17	42	22		1		25	107
All hours ..	No.				56	161	73	5	4	6	111	416
	%				*13*	*39*	*18*	*1*	*1*	*1*	*27*	
SEPTEMBER.												
6 — 9 hrs. ..	..				2	23	12	3		16	58	114
10—12 hrs. ..	..				12	23	16	2	1		20	74
13—15 hrs. ..	..				8	16	19	2	2		22	69
15 hrs. to sunset	..				8	16	25	3	1		37	90
All hours ..	No.				30	78	72	10	4	16	137	347
	%				*9*	*22*	*21*	*3*	*1*	*5*	*40*	
ALL MONTHS (JUNE—SEPTEMBER.)												
6 — 9 hrs. ..	No.				11	116	54	7	1	32	198	419
	%				*3*	*28*	*13*	*2*		*8*	*47*	
10—12 hrs. ..	No.			1	64	136	54	3	2		59	319
	%				*20*	*43*	*17*	*1*	*1*		*18*	
13—15 hrs. ..	No.			1	50	86	52	11	4		77	283
	%				*18*	*30*	*18*	*4*	*1*		*27*	
15 hours to sunset	No.			1	58	114	72	9	3		110	357
	%				*16*	*32*	*20*	*2*	*1*		*31*	
All hours ..	No.			3	183	452	232	30	10	32	444	1,378
	%				*13*	*33*	*17*	*2*	*1*	*2*	*32*	

TABLE 2.—*Summary of low cloud height measurements at Bombay (1932-34).*

		Height of cloud in metres above ground.								No low cloud.	Height not determined due to other causes.	No. of observations.
		0-99.	100 to 199.	200 to 299.	300 to 599.	600 to 999.	1000 to 1499.	1500 to 1999.	2000 to 2499.			
JUNE.												
6 — 9 hrs. ..	..					1						1
9 —12 hrs. ..	..				11	9	6	2			1	29
12—14 hrs. ..	..				5	7	2					14
14 hrs. to sunset	..	..			13	8	7				1	29
All hours ..	No.				29	25	15	2			2	73
	%				*40*	*34*	*21*	*3*			*3*	
JULY.												
6 — 9 hrs. ..	..			1	13	13	1				2	30
9 —12 hrs. ..	..				12	21	6					39
12—14 hrs. ..	..		1		7	15	1					24
14 hrs. to sunset	..		1	3	24	32	16	3				79
All hours ..	No.		2	4	56	81	24	3			2	172
	%		*1*	*2*	*33*	*47*	*14*	*2*			*1*	
AUGUST.												
6 — 9 hrs. ..	..			1	18	17	4				3	43
9 —12 hrs. ..	..			1	14	14	15	2	1		3	50
12—14 hrs. ..	..				4	6	6	2			3	21
14 hrs. to sunset	..			1	11	25	12	1			7	57
All hours ..	No.			3	47	62	37	5	1		16	171
	%			*2*	*27*	*36*	*22*	*3*			*10*	
SEPTEMBER.												
6 — 9 hrs. ..	..				6	6	10	1			2	25
9 —12 hrs. ..	..				8	14	9	1			6	39
12—14 hrs. ..	..				6	4	1	1			2	14
14 hrs. to sunset	..			2	6	12	12	5			3	40
All hours ..	No.			2	26	36	32	8	1		13	118
	%			*2*	*22*	*31*	*27*	*7*	*1*		*11*	
ALL MONTHS (JUNE—SEPTEMBER).												
6 — 9 hrs. ..	No.			2	37	37	15	1			7	99
	%			*2*	*37*	*37*	*15*	*1*			*7*	
9 —12 hrs. ..	No.			1	45	58	36	5	2		10	157
	%			*1*	*29*	*37*	*23*	*3*	*1*		*6*	
12—14 hrs. ..	No.		1		22	32	10	3			5	73
	%		*1*		*30*	*44*	*14*	*4*			*7*	
14 hrs. to sunset	No.		1	6	54	77	47	9			11	205
	%			*3*	*26*	*38*	*23*	*4*			*5*	
All hours ..	No.		2	9	158	204	108	18	2		33	534
	%			*2*	*30*	*38*	*20*	*3*			*6*	

TABLE 3.—*Summary of low cloud height measurements at Madras (1933-36.)*

		Height of cloud in metres above ground.										
——		0·99.	100 to 199.	200 to 299.	300 to 599.	600 to 999.	1000 to 1499.	1500 to 1999.	2000 to 2499.	No low cloud.	Height not determined due to other causes.	No. of observations.
OCTOBER ('33—'35).												
6 — 9 hrs. ..	..					7	7	2	2	36	2	86
9 —12 hrs. ..	..			3	6	18	12	4	1		9	53
12—14 hrs. ..	..				9	16	6	3		6	30	70
14 hrs. to sunset	..				5	11	1	2	1	8	3	61
All hours ..	No.			3	20	52	26	11	4	50	104	270
	%			*1*	*7*	*19*	*10*	*4*	*1*	*18*	*38*	
NOVEMBER ('33—'35)												
6 — 9 hrs. ..	..					6	11	1	5	25	40	88
9 —12 hrs. ..	..				16	21	14	1		1	7	60
12—14 hrs. ..	..				13	19	4	1			19	56
14 hrs. to sunset	..				1	9	15	4	1	15	44	89
All hours ..	No.				30	55	44	7	6	41	110	293
	%				*10*	*18*	*15*	*2*	*2*	*14*	*38*	
DECEMBER ('33—'35)												
6 — 9 hrs. ..	..				2	4	7	8	2	15	59	92
9 —12 hrs. ..	..		1	1	12	29	8	5			11	67
12—14 hrs. ..	..				11	26	13	2			11	63
14 hrs. to sunset	..				2	8	20	3		5	52	90
All hours ..	No.		1	1	27	67	48	13	2	20	133	312
	%				*9*	*21*	*15*	*4*	*1*	*6*	*43*	
JANUARY ('34—'36).												
6 — 9 hrs. ..	..				1	5	5	2		22	56	91
9 —12 hrs. ..	..				13	22	10	3		1	9	58
12—14 hrs. ..	..			1	8	16	11	1	1		12	50
14 hrs. to sunset	..				2	17	9	3		16	46	93
All hours ..	No.			1	24	60	35	9	1	39	123	292
	%				*8*	*20*	*12*	*3*		*13*	*42*	
ALL MONTHS (OCTOBER—JANUARY)												
6 — 9 hrs. ..	No.				3	22	30	8	9	98	187	357
	%				*1*	*6*	*8*	*2*	*3*	*27*	*52*	
9 —12 hrs. ..	No.		1	4	47	90	44	13	1	2	36	238
	%			*2*	*20*	*38*	*18*	*5*		*1*	*15*	
12—14 hrs. ..	No.			1	41	77	34	7	1	6	72	239
	%				*17*	*32*	*14*	*3*		*3*	*30*	
14 hrs. to sunset..	No.				10	45	45	12	2	44	175	333
	%				*3*	*13*	*13*	*4*	*1*	*13*	*53*	
All hours ..	No.		1	5	101	234	153	40	13	150	470	1,167
	%				*9*	*20*	*13*	*3*	*1*	*13*	*40*	

TABLE 4.—*Frequencies (numbers) of low cloud height at Poona at night. (Observations generally between 20 and 21 hrs. during 1935, 1937 and 1938.)*

—	0-49.	50 to 99	100 to 199	200 to 299	300 to 599	600 to 999	1000 to 1499	1500 to 1999	2000 to 2499	No low cloud.	Observations not taken.*
(*a*) Using *mean* of several readings on each night.											
July					2	30	19	3		7	32
August					3	17	27	10	3	17	16
September			1		3	16	8	9		19	34
(*b*) Using *lowest* of several readings on each night.											
July				5	4	36	6	3		7	32
August				6	4	34	13	2	1	17	16
September			2	1	9	17	3	6		17	35

* Some of these may have been without low clouds also.

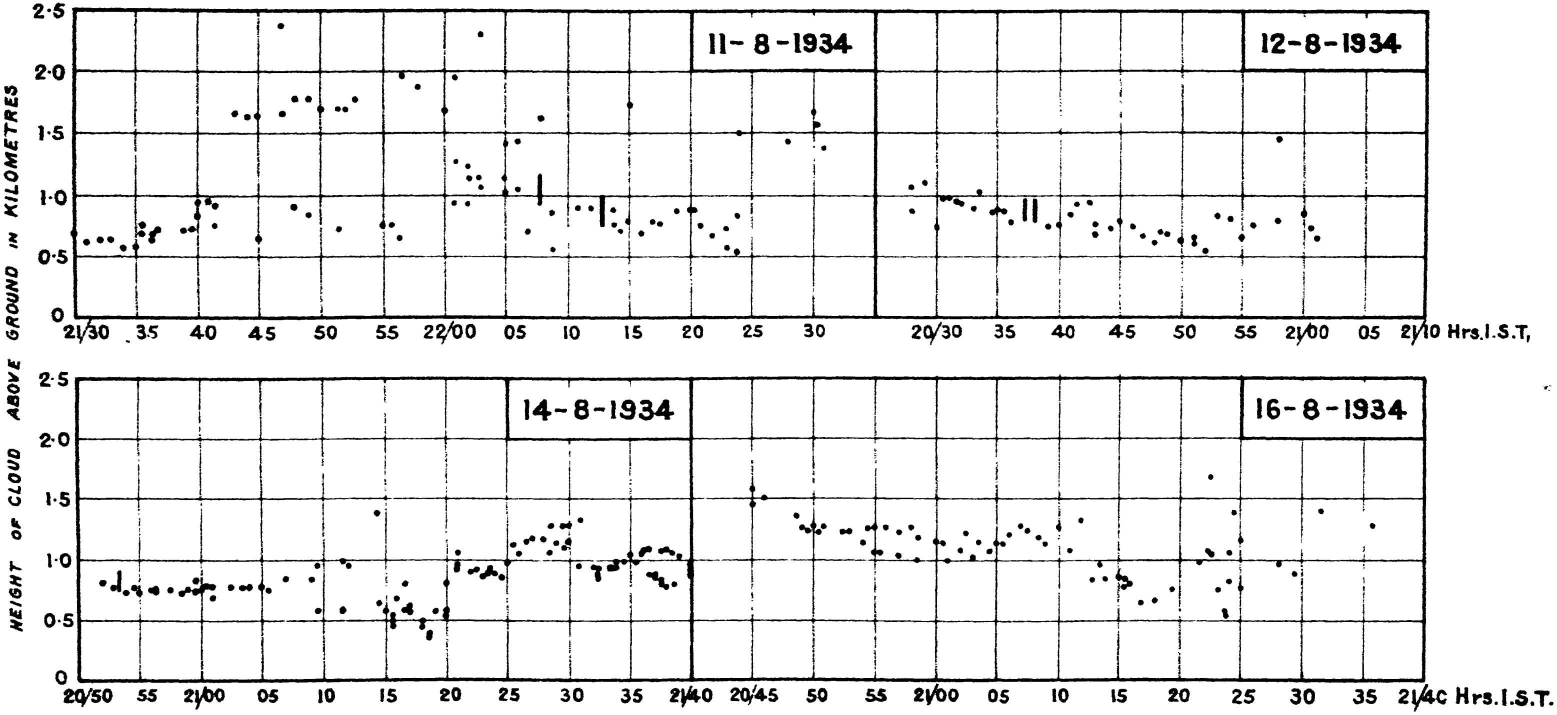

Fig. 1. Heights of cloud at Poona on 4 nights in August, 1934, determined by means of a search-light.

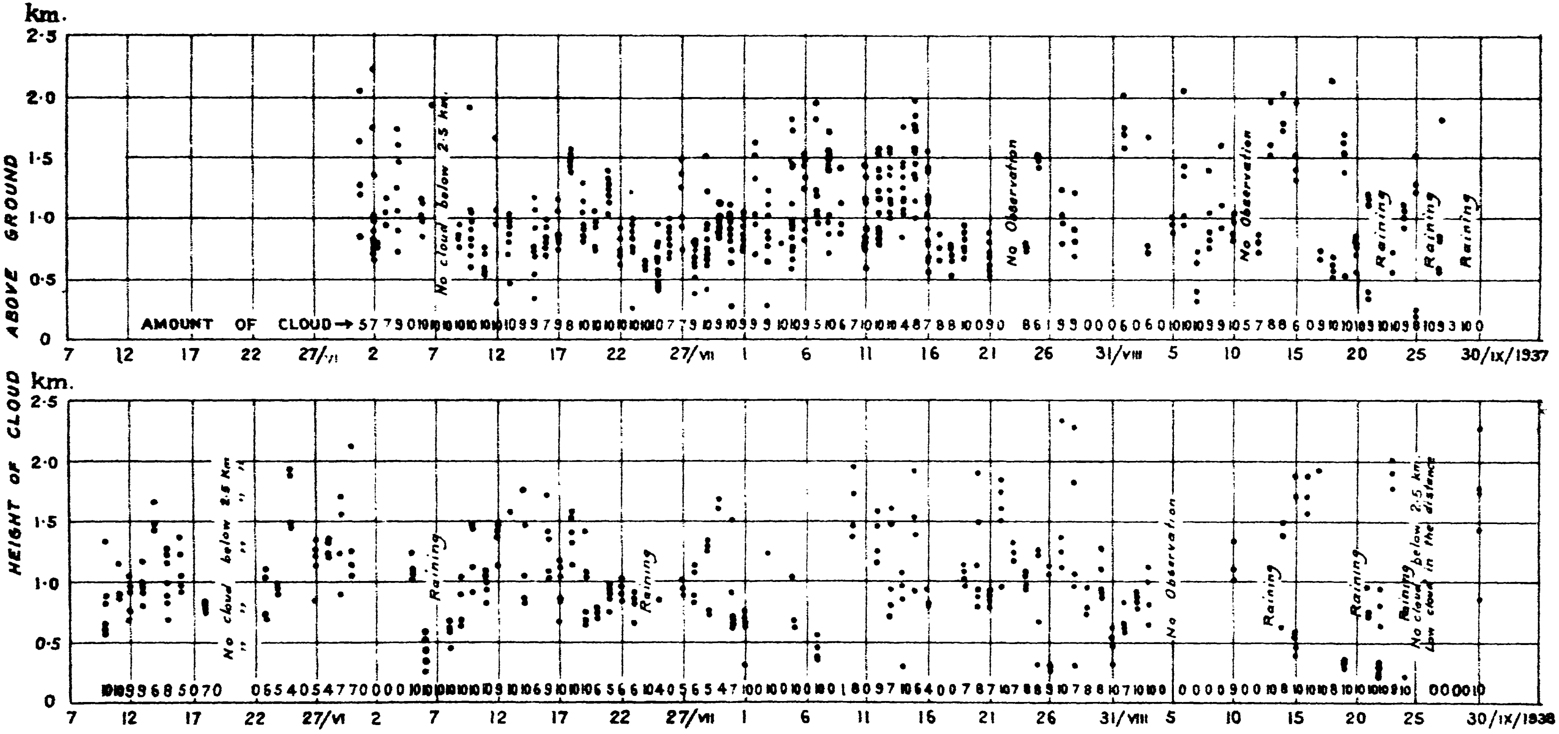

Fig. 2. Heights of cloud at Poona on each night (between 20 and 21 hrs.) in the monsoon seasons of 1937 and 1938, determined by means of a searchlight.

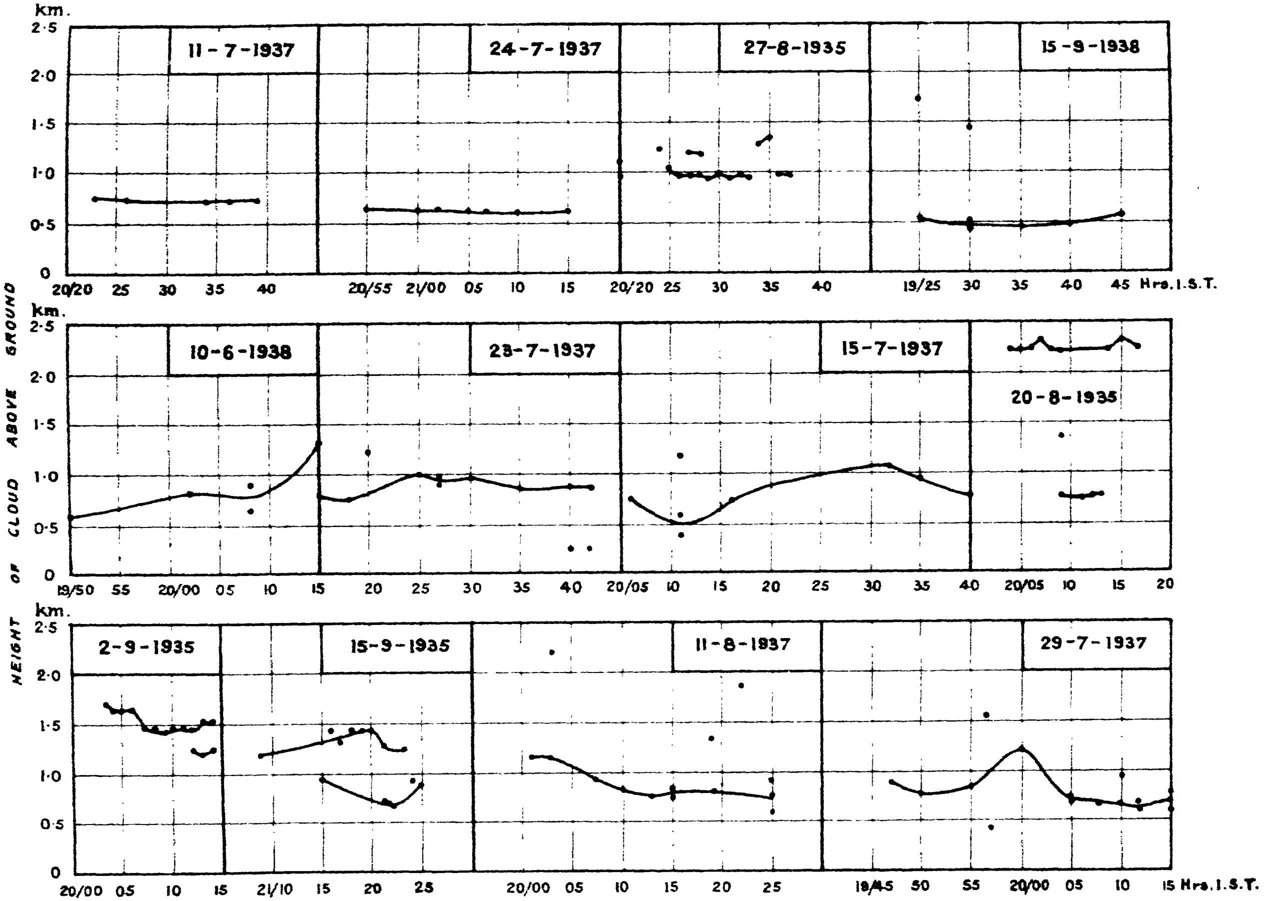

Fig. 3. The variation of height of cloud at Poona within the time of observation, 20 to 21 hrs., on some typical nights in the monsoons of 1935, '37 and '38, determined by means of a searchlight.

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INDIA METEOROLOGICAL DEPARTMENT

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Determination of Visibility at night with the help of Wigand's or Bennett's visibility meter.

BY

A. K. ROY.

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DETERMINATION OF VISIBILITY AT NIGHT WITH THE HELP OF WIGAND'S OR BENNETT'S VISIBILITY METER.

BY

A. K. Roy.

(Received on 3rd April 1939.)

Abstract.—The paper* gives a simple method of determining the visibility code figure at night with the help of a Wigand's or Bennett's visibility meter and two landmark lamps of low candle power at short distances from the observatory

By calibrating the visibility meter, according to the method described in the paper, it is seen that the curve obtained by plotting n against $\log I$ is approximately a straight line, showing that the obscuring power of filter marked n is equal to that of n filters marked 1. With the help of the calibration curve a table has been drawn up which gives the meter readings corresponding to the different grades of filters that would be required to reduce the intensity of illumination from the two landmark lights to the limiting value for vision, under different conditions of visibilty.

The observation of visibility consists simply in viewing the two lights by turn through the visibility meter and in noting the meter readings at which the lights are just made invisible. From the meter readings thus obtained one finds the visibility at the time of observation by reference to the table mentioned above.

The inauguration of regular night flying along air routes made it necessary for the meteorological organisations in different countries to adopt a standardised procedure for the observation of visibility at night. Experiments were therefore undertaken in India to evolve standard methods of observation suited to conditions in this country. The note records the results of the experiments which were carried out in 1936 and formed the basis of the instructions that are being followed at present at a number of observatories in India for night visibility observations.

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* Since this paper was communicated for publication the author has seen the recent article by E. Gold in the Q. J. R. Met. Soc. for April 1939, which describes a method of ascertaining the visibility number V at night from observation of two near lamps with the help of a specially constructed meter.

The international conference held at Warsaw in 1935 made the following provisional recommendation regarding the scale of distances of lights of known intensity, to be used as landmarks for determination of visibility from 0 to 9.

V	*A*.			*B*.
0	0·13 c. p.	at	50 m.	100 m.
1	0·9 ,,	,,	200 ,,	330 ,,
2	3·5 ,,	,,	500 ,,	740 ,,
3	10 ,,	,,	1,000 ,,	1,340 ,,
4	35 ,,	,,	2,000 ,,	2,300 ,,
5	100 ,,	,,	4,000 ,,	4,000 ,,
6	420 ,,	,,	10 km.	7½ km.
7	1,250 ,,	,,	20 ,,	12 ,,
8	4,500 ,,	,,	50 ,,	At greater distances a 100 c.p. is not suitable.
9	about 20,000 c.p.	at	150 km.	

A.—If lights at the same distances as objects during day are to be used they must be of the c.p. as specified under *A*.

B.—If lights of fixed intensity of 100 c.p. are used they must be at the distances mentioned under *B*.

It will be seen from the above that if 100 c.p. lights are used, they have to be fixed at distances beyond 7 kms. for visibilities 6 or above. The fixing of lights at such great distances would involve considerable practical difficulties at most stations in India, and it was thought that the adoption of lights of lower candle power would be more convenient.

The scale of distances for lights of 1 c.p. (calculated according to the relation $I' = \frac{I}{d^2}10^{-kd.}$ where k. is the absorption coefficient per km. under a given condition of visibility and d is the distance in km.) is given in the following table. The calculations have been made assuming 0·1 c.p./km.^{2} as the value for threshold illumination I'.

TABLE I.

Visibility in code figure.	Distances of 1 c.p. light.
0	70 yds.
1	225 ,,
2	450 ,,
3	740 ,,
4	1,140 ,,
5	1,650 ,,
6	1⅛ miles
7	1½ ,,
8	1¾ ,,

Even in this case, the distances of landmark lights for visibility 6 and above would be about 2 kms. and more, and at many places in India the installation and working of standard lights at such distances would present practical difficulties. It was therefore considered whether the use of a suitable visibility meter would provide us with some convenient method of determining visibility at night with the help of one or two lights only near about the observatory.

The straightforward method of calibrating a visibility meter would obviously be to have a light of known intensity at a fixed distance from the observatory and note the readings of the particular grade of filter which would cut out the light under different visibility conditions. As, however, it was not practicable for the purposes of such calibration to wait and watch for occasions of low visibility at night which occur only very infrequently at Poona where the experiments described in this note had to be done, it was not possible to calibrate a visibility meter by any such direct method. The following indirect method was therefore adopted for the calibration.

Seven candle lamps of about 0·7 c.p. (10 oz. candles) were fixed in different directions at the following distances from the place of observation.

Lamp 1 at 69 yds. or ·063 km.
„ 2 at 226 „ or ·207 „
„ 3 at 451 „ or ·41 „
„ 4 at 738 „ or ·67 „
„ 5 at 1,140 „ or 1·04 „
„ 6 at 1 mile or 1·6 „
„ 7 at 1½ miles. or 2·4 „

Each of these lamps was observed through Wigand's and Bennett's visibility meters and the reading of the instrument, that is, the grade of filter which made each of these invisible was noted.

On all the days on which the above experiments were carried out the visibility, as estimated by eye in the evening with the help of standard landmarks, was 8. Observations were made in the early part of night, and the visibility at the time was taken to be the same as in the evening. On the first two or three days, when 12 oz. candles were being used for the experiment, there was a difficulty in keeping the candles burning steadily, for, the springs inside the holder often failed to act and did not push the candle up uniformly and, as a result, the light gradually became dim and eventually went out. The difficulty was overcome by using thinner candles, that is, 10 oz. ones. The candle power of the lights then remained more or less constant during the period of the experiments.

Further, on the first two days, there was in some cases an appreciable difference between the readings taken by the author and those taken by the other observers who assisted in the observations. Later on, however, with practice, the readings agreed very much better, and the readings taken by the author and those taken by the observers were the same in most cases. The values of n (that is, the readings of the visibility meters) with respect to the seven different lamps are given in *Table II*. Except in the cases of 6th and 7th lamps for which the readings sometimes varied by ±1, the values of n were in most instances the same as given in the table.

TABLE II.

	1st lamp.	2nd lamp	3rd lamp.	4th lamp.	5th lamp.	6th lamp.	7th lamp.
n (Wigand) ..	>15	14	11	9	7	5	4
n (Bennett) ..	19	15	12	10	8	6	5

Table III below gives the values of the intensity of illumination at the point of observation due to the seven different lamps when visibility is 8, as calculated from the equation

$$I_{n_{(8)}} = \frac{0\cdot7}{d^2}\, 10^{-kd} \quad \cdots \quad \cdots \quad \cdots \quad \cdots \quad (1)$$

$$= \frac{0\cdot7}{d^2}\, 10^{-.027d}$$

For calculation of the intensity, k has been taken as $\cdot027$ per km., the lowest accepted value of absorption coefficient of air for $V = 8$.

TABLE III.

$I_{1(8)} = 175\cdot7$ c. p. /km.^{2}

$I_{2(8)} = 16\cdot13$,,

$I_{3(8)} = 4\cdot06$,,

$I_{4(8)} = 1\cdot49$,,

$I_{5(8)} = \cdot606$,,

$I_{6(8)} = \cdot247$,,

$I_{7(8)} = \cdot105$,,

where $I_{1(8)}$ is the intensity of illumination due to the 1st lamp, $I_{2(8)}$ due to the 2nd, and so on.

Now if α is the absorption coefficient of filter No. 1, and I and I' are the intensities of illumination at the point of observation before and after passage through the filter marked n, then it is assumed that

$$I' = I.\, 10^{-n\alpha} = I.A.^{n} \text{ where } A = 10^{-\alpha}$$

Thus, if the meter reading at which the 7th lamp becomes just invisible is n_7 and that at which the 6th lamp becomes invisible is n_6

$$I_{7_{(8)}} A^{n_7} = I_{6_{(8)}} A^{n_6} \quad \cdots \quad \cdots \quad \cdots \quad \cdots \quad (2)$$

or $I\, A^n$ = constant = B (the threshold value for vision), I being the intensity of illumination at the point of observation

$$\text{or } \log I + n \log A = \log B \quad \cdots \quad \cdots \quad \cdots \quad \cdots \quad (3)$$

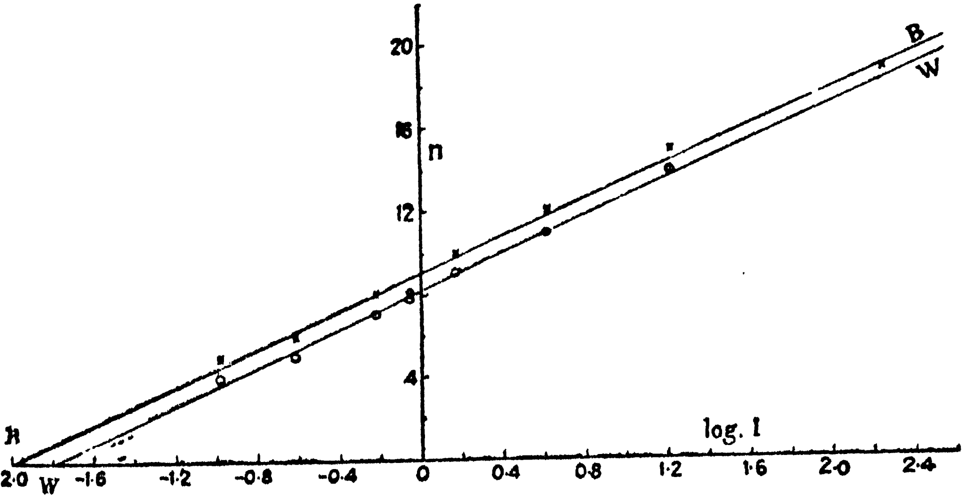
or $x + my = C$, where $\log I = x$, $\log A = m$, $n = y$ and $\log B = C$.

The values of x ($\log I$) and the corresponding observed values of y (n) for the different lamps are given in the table below.

TABLE IV.

	$x = \log I$.	$y = n$ (Wigand).	$y = n$ (Bennett).
7th lamp	—·98	4	5
6th lamp	—·606	5	6
5th lamp	—·217	7	8
4th lamp	+·173	9	10
3rd lamp	+·608	11	12
2nd lamp	+1·207	14	15
1st lamp	+2·245	>15	19

The observed values of y were plotted against the corresponding values of x (as given in the above table), and the two curves thus obtained gave the calibration curves of the Wigand's and Bennett's instruments. The curves WW (Wigand) and BB (Bennett), obtained as above, and shown in *figure below* are straight lines, which shows that the assumption made in deriving (2) and (3) is justified.



CALIBRATION CURVES OF WIGAND'S AND BENNETT'S VISIBILITY METERS

The values of A and B can then be obtained from the above curves. From the calibration curve of Wigand's instrument it is found that

$m = \log A = -{\cdot}217$

or $A = {\cdot}61$ approximately.

Also, $O = \log B = OW = -1{\cdot}78$

or B is of the order ·016.

Similarly, from the calibration curve of Bennett's instrument, the value of $m = \log A$ is found to be $-\cdot 222$

or $A = \cdot 60$ approximately.
Also, $C = \log B = OB = -2\cdot 0$
or $B =$ about $\cdot 01$.

From the values of B as obtained above it appears that the threshold value lies between ·01 and ·02 c.p./km.^{2} which is much less than the value 0·1* that has been adopted by the International conference at Warsaw for calculation of the distances of 100 c.p. lamps to be used as landmarks in connection with night visibility measurements. It is obvious that the threshold value will be different, according as we adopt as our criterion either (1) the recognition of the mere presence of a light or (2) the recognition of a light by resolution of distinguishing details of the source of illumination. The threshold value in the latter case is expected to be quite different and perhaps appreciably larger than in the former case. The value of about 0·1 for threshold illumination, accepted by Bennett, refers, it is believed, to the latter criterion, and applies to the eye under normal condition, that is, to an eye which is not under strain but is merely adapted to darkness for some time. The values as obtained by the above experiments, on the other hand, refer to the former criterion, for, in these experiments a light was considered to be visible until the interposition of a series of ground glasses in the line of vision reduced the intensity of light to such an extent that it was impossible to detect the presence of the known source of light inspite of straining the eye to the utmost.

The values of n that thave been used for the above calibration were obtained on evenings when there was no moon light. These values may be somewhat different if observations are taken in moonlit nights when the threshold value would be somewhat higher. A set of observations taken on one evening, when there was moonlight, however showed no difference in the value of n, except in the case of the 7th lamp for which both n_W and n_B (the readings respectively of Wigand's and Bennett's visibility meters at which the light was just made invisible) were less than those found previously by observation in dark nights.

From the calibration curves, as described above, one is in a position to determine the value of n for any light of known intensity at a fixed distance, under different visibility conditions. In order to verify that the calibration carried out as above with 0·7 c.p. lamps holds good for stronger lights also, three electric lights of 2·5, 4·0 and 12·5 c.p. were fixed at a distance of 1·04 km. from the point of observation. The calculated as well as the observed values of n_W and n_B are given below.

TABLE V.

C.p. of lamp.	n_W (Cal.).	n_W (Obs.).	n_B (Cal.).	n_B (Obs.).
2·5	9·7	10	11	12
4·0	11·0	12	12	13
12·5	13·2	14	14	16

The above table shows that the observed values of n are slightly higher than the calculated values ; but the difference is small and it appears that the curves can be accepted to hold approximately for stronger lights also.

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* According to Luckiesh and Moss, the absolute minimum perceptible intensity in complete darkness is however about 0·1 c.p. at 10 km. or ·001 c.p./km.^{2} only.

The following table gives the calculated values of log I and also of n_W and n_B for seven lamps of 1 c.p. at distances ·063, ·207, ·41, ·67, 1·04, 1·6 and 2·4 kms. under different visibility conditions, as read off from the calibration curves. In obtaining the values of n_W and n_B in the table below, only the minimum absorption coefficient of air corresponding to a particular code figure V has been considered. As, however, the absorption coefficient for visibility given by the same code figure is not constant but varies within certain limits, n_W and n_B would also have corresponding variations, with values lying between those shown against the particular code figure and the next lower one.

TABLE VI.

—	Visibility.	*Log. I.*	n_W.	n_B.
1st lamp at a distance of ·063 km	8	2·4	>15	20
	7	2·4	>15	20
	6	2·39	>15	20
	5	2·37	>15	19·9
	4	2·34	>15	19·8
	3	2·28	>15	19·5
	2	2·13	>15	18·8
	1	1·66	>15	16·6
	0	—·98	3·7	4·6
2nd lamp at a distance of ·207 km	8	1·36	14·6	15·3
	7	1·35	14·5	15·2
	6	1·33	14·4	15·1
	5	1·28	14·2	14·9
	4	1·17	13·7	14·4
	3	·96	12·6	13·5
	2	·49	10·5	11·3
	1	—1·05	3·5	4·3
3rd lamp at a distance of ·41 km.	8	·76	11·8	12·6
	7	·74	11·7	12·5
	6	·71	11·5	12·3
	5	·6	11	11·8
	4	·39	10·1	10·8
	3	—·04	8·1	8·9
	2	—·97	3·8	4·7
4th lamp at a distance of ·67 km.	8	·33	9·8	10·6
	7	·3	9·6	10·4
	6	·24	9·4	10·2
	5	·058	8·5	9·4
	4	—·273	7	7·8
	3	—·99	3·8	4·6
5th lamp at a distance of 1·04 km	8	—·062	8	8·8
	7	—·11	7·8	8·6
	6	—·2	7·4	8·2
	5	—·48	6·1	6·9
	4	—1	3·7	4·6
6th lamp at a distance of 1·6 km.	8	—·45	6·2	7·1
	7	—·52	5·9	6·8
	6	—·66	5·3	6·1
	5	—1·06	3·4	4·2
7th lamp at a distance of 2·4 km.	8	—·83	4·4	5·4
	7	—·94	4	4·8
	6	—1·14	3	4
	5	—1·8	0	1

Thus, if we have one or more lights of 1 c.p. at distances as specified above, and if one of them is seen through a visibility meter, the meter reading giving the grade of filter which cuts out the light completely will give us an idea of visibility at the time of observation.

It will be seen from the above table that the values of n do not differ appreciably for change in visibility from 8 to 6, particularly in the case of near lamps. For instance, in the case of the 4th lamp, n_B varies from 10·6 to 10·2 for variation in visibility from 8 to 6. But as the instrument has graduations in whole numbers only, it will give the same reading 11, for visibilities ranging from 8 to 6. The value of n_B, however, changes more rapidly for poorer visibilities and is 10 or 9 for visibility 5, 8 to 6 for visibility 4, 5 to 1 for visibility 3 and 0 for 2 or less. If the value of n_B in the case of the 4th lamp is less than 1, it becomes necessary to see a nearer light through the visibility meter in order to ascertain whether the visibility is 2, 1 or 0. If the 2nd lamp at a distance of ·207 km. is used as the nearer landmark, and if this is now seen through the visibility meter

for visibility 2, n_B will be between 12 and 6
for visibility 1, n_B will be between 5 and 1
for visibility 0, n_B will be less than 1.

Thus with two lamps of 1 c.p. as landmarks at distances of ·207 and ·67 km. and a Bennett's visibility meter it would be possible to determine visibilities 0, 1, 2, 3, 4, 5 and 6 to 8. In order to be able to say whether visibility at any time is 6, 7 or 8, it would be necessary to have a distant lamp, such as, a lamp of 1 c.p. at 1·6 km. If n_B for this lamp is 7, visibility is 8 or 7, and if it is 6, visibility is 6.

As, however, for all practical purposes in connection with night flying, it may not be as important to make a strictly accurate determination of visibility when it is 6 or more as when visibility is less than 6, the use of the distant lamp may be dispensed with if it is found difficult to arrange for its installation, and the observers may be asked to make as good an eye estimate as may be possible for visibilities ranging from 6 to 9.

It was noticed in the course of observations that if a light stronger than that used as landmark was in view through the Wigand's visibility meter at the same time as the landmark light itself, it was difficult to get the correct value of n, and the filter reading actually noted in such a case was appreciably lower than the true value. It is therefore essential, if a comparatively weak source of light be used as our landmark, that there should be no other stronger light within an angular distance of about 10° from the landmark lamp. This difficulty, however, is not so pronounced in the case of the Bennett's meter in which the long tube in front of the instrument restricts the field of vision within the limits of a very small angle. The use of this tube, however, presents another difficulty, *viz.*, that while holding the instrument in hand and operating the keys, if the tube is tilted even slightly from the line of vision, the light will no longer be in view and the observer, if not careful, may erroneously consider that the light has actually been made invisible by the filters already interposed by him. In order to be sure that an error of this kind does not occur, the observer should, after the light is made invisible, continue to hold the instrument steadily in the same position and release one or more of the keys and then see whether the light is again visible through the tube. If so, he should again begin to operate the keys and interpose the proper numbers of filters until the light is no longer visible. It is desirable to repeat the observation at least three times and then note the correct number of filters as marked on the keys.

The author desires to express his thanks to the Director General of Observatories for the facilities given to him in carrying out the above experiments and to Mr. Barkat Ali for some helpful suggestions and criticisms. His thanks are also due to Mr. N. C. Mukherji for his help in taking the observations.

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INDIA METEOROLOGICAL DEPARTMENT

SCIENTIFIC NOTES

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A Discussion of some Aeroplane Ascents at Drigh Road (Karachi) on days of Duststorms, Thunderstorms and Dust Raising Winds.

BY

B. N. DESAI AND S. MAL.

(*Received on 21st December 1937.*)

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A DISCUSSION OF SOME AEROPLANE ASCENTS AT DRIGH ROAD (KARACHI) ON DAYS OF DUSTSTORMS, THUNDERSTORMS AND DUST-RAISING WINDS.

BY

B. N. DESAI AND S. MAL.

(*Received on 21st December 1937.*)

Abstract.—Some aeroplane ascents at Drigh Road on days of dust-storms, thunderstorms and strong dust-raising winds have been examined with a view to understand the agency which initiates them. It is observed that although knowledge about latent instability gained from the data of aeroplane ascents in the morning helps to predict the occurrence of dust or thunderstorms later in the same day, when the weather situation is not rapidly changing, there are occasions on which disturbances are passing over the station or are persisting near it, when latent instability conditions probably change and the data of earlier aeroplane ascents alone do not help in predicting the likely development of weather unless the morning upper air data are considered with due reference to the meteorological conditions prevailing over the surrounding regions. The inference drawn in a previous paper that at Karachi, on days of latent instability insolation alone generally produces only thundery conditions* and not a full-fledged thunderstorm or duststorm at Drigh Road is also supported. The other factors which are believed to have acted as triggers for the release of energy of latent instability in the cases examined are—

(1) The arrival of cold air in connection with the passage of a cold front,

(2) the convergence of winds due to nearness of a surface of discontinuity, and

(3) the flow of cold air from an adjoining thunderstorm.

It is observed, as is to be expected, that neither latent instability nor superadiabatic gradients are specially associated with the occurrence of dust-raising winds reducing the visibility to code figure 4 or less.

In a previous paper[1] the authors have discussed the spell of thundery conditions over Drigh Road in June-July 1936 with reference to available aeroplane ascents and suggested the conditions, a knowledge of which can enable one to foresee with a reasonable chance of success the occurrence of thundery conditions over the Air Port. Rao[2] has examined the squalls at Karachi and concluded that during the summer and monsoon period when other conditions are favourable and latent and convective instability conditions exist in the lower levels, the afternoon insolation probably acts as the ' trigger ' providing the necessary initial amount of energy required to make the energy of instability realisable. From an examination of the available records of soundings at Agra of duststorm conditions from the point

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* Distinction between " thundery conditions " and " thunder or duststorm " is based on the accompanying wind force at ground. The term thunder or duststorm has been used only for occasions when the accompanying ground wind had force 6 or more on the Beaufort scale. This distinction is important from the point of view of forecasting for aviators.

of view of latent instability, Sreenivasaiah and Sur[3] *have shown that the occurrence of duststorms is mostly associated with the existence of a state of latent instability in the atmosphere. The mere existance of latent instability is not, however, sufficient to cause the phenomenon unless a suitable agency or trigger of sufficient strength is there to give initial displacement necessary to lift the layer of air possessing latent* instability into that part of the environment where it will gain energy. In the present paper some aeroplane ascents at Drigh Road prior to 1936 on days of duststorms, thunderstorms and strong dust raising winds there have been discussed with a view to understand their probable mechanism. Four of these ascents, *viz.*, those on the 24th and 29th March 1932 and 8th and 12th July 1932 have been discussed by Mr. Rao[2] in his paper. The view point in this paper is however somewhat different from Mr. Rao's.

1. Duststorm and thunderstorm of 27th November 1928.

A western disturbance lay just to the north of Mekran on the 27th morning. Upper winds over Drigh Road that morning were blowing from a westsouthwesterly direction, the force being light to moderate up to 2 Km. and generally strong above that height up to 5 Km.

The sky was overcast with stratus at 0900 hrs. I.S.T. There was an aeroplane ascent about 2 hours afterwards and the data of the same are plotted in *Fig. 1,* ABCDE and FGHIJ being the tephigram and W.B. curve respectively.

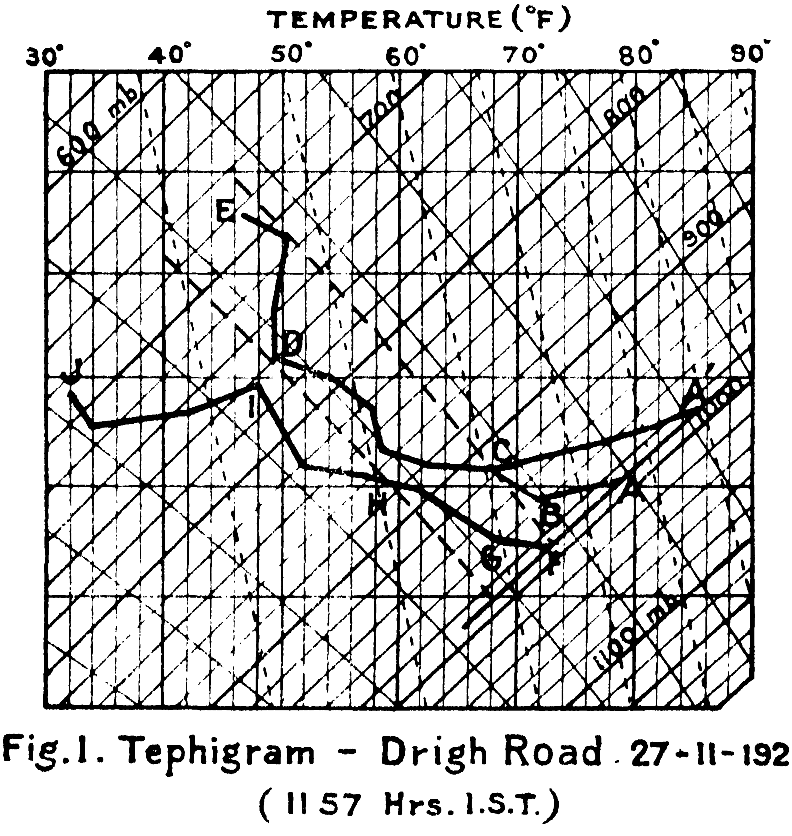

Fig. 1. Tephigram - Drigh Road 27-11-1928.

(1157 Hrs. I.S.T.)

From the figure it is obvious that although there was latent instability in the first 110 mbs., the air layers between the surface and 950 mbs. (*i.e.,* the first 40 mbs.) only could release appreciable energy. The maximum temperature that afternoon was 85°F. and the afternoon tephigram would thus be roughly A'CDE*; the W.B. at the time of the maximum was the same as that at the time of ascent. It will be seen that insolation could have raised the air in the first 70 mbs. to such an extent as to enable it to release its energy of latent instability. At 1500 hrs. there was a pilot balloon ascent but the balloon could not be followed above 1 Km., the sky being overcast with cumulonimbus ; the upper winds up to 1 Km. were generally moderate southwesterly and the cloud was also moving from that direction. The development of stratus into KN was probably due to insolation, but evidently the energy so liberated was not sufficient for the generation of a thunderstorm as no thunderstorm was experienced up to 1930 hrs.

There was slight rain at Drigh Road between 1830 and 1930 hrs. and after 1930 hrs. a dust-storm with squally winds immediately followed by thunder, lightning and intermittent rain was recorded. Pasni had thunder and lightning after 1215 hrs. that afternoon with 2" of rain during the thunderstorm between 1430 and 1530 hrs., Panjgur had a duststorm between 1130 and 1315 hrs. followed by rain and hailstorm between 1315 and 1430 hrs. and Ormara had slight showers of rain between 1525 and 1600 hrs. and a thunderstorm between 1730 and 1930 hrs. It has been mentioned before that a western disturbance lay just to the north of Mekran on the 27th morning and it can be concluded that the weather experienced at Pasni, Panjgur and Ormara was in connection with the cold front of that disturbance which by 0800 hrs. of the 28th lay over the Punjab. The cold front apparently passed Ormara between 1730 and 1930 hrs. During its passage over Baluchistan the cold front at the ground will be considerably retarded and distorted due to the hilly nature of the country (the height of many hills being at least about 3,000 feet above sea level) and the associated cold air at levels higher than the tops of the hills will move considerably in advance than at lower levels. This will cause a lowering of dry bulb temperature in the upper levels earlier than at the surface [shifting of the D.B. curve (*Fig. 1*) towards the left] and consequently the development of increased latent instability. When the cold air arrives at the surface it will act as a trigger for the release of the energy of latent instability and consequently development of dust or thunderstorm. From the autographic records of Drigh Road for this day which have been given in the book of the "Meteorology of the Persian Gulf and Mekran" by B. N. Banerji[4], it is seen that when the dust and thunderstorm occurred, the wind veered to WNW from SW and there was a fall in the D.B. by about 13°F.

It will appear from the foregoing discussion that although ordinarily no thunderstorm could have occurred at Drigh Road due to want of a high degree of latent instability as judged from the morning ascent, conditions changed due to the movement of the cold front of the western disturbance and a dust and thunderstorm occurred.

2. Thundery conditions of 5th October 1931.

On the 5th morning there was a low over the north Deccan which had moved there from the Bay of Bengal. The upper winds over Drigh Road were generally moderate and from NNE to ENE at least up to 4 Km.

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*Distribution of dry-bulb and wet-bulb temperatures with height at the time of maximum has been obtained by using the maximum tmeperature and the corresponding wet-bulb from the autographic records. If the superadiabatic gradients in the layers above the surface were larger or smaller at the time of the maximum than those indicated by the curve A'C (*Fig. 1*), they would not increase the thickness of the layer from which energy of latent instability could be realised due to insolation alone, although there would be changes in the amount of energy so realised. In all the cases except on the 12th July 1932 (*Fig. 6*), the distribution of wet-bulb in the lower levels at the time of the maximum is such that the wet-bulb decreases with height. It is quite possible that in these cases the wet-bulb might be first increasing with height and then decreasing as on the 12th July 1932 (*Fig. 6*) ; this would increase the amount of energy realised. Such changes in the distribution of dry-bulb and wet-bulb temperatures would not, however, materially affect our conclusions.

At Drigh Road there were passing clouds from 0600 to 0900 hrs. The sky was clear between 0900 and 1100 hrs. when an aeroplane ascent was also made and some clouds appeared again. The results of the ascent are plotted in *Fig. 2,* ABC and DEFG being the D.B. and W.B. curves respectively.

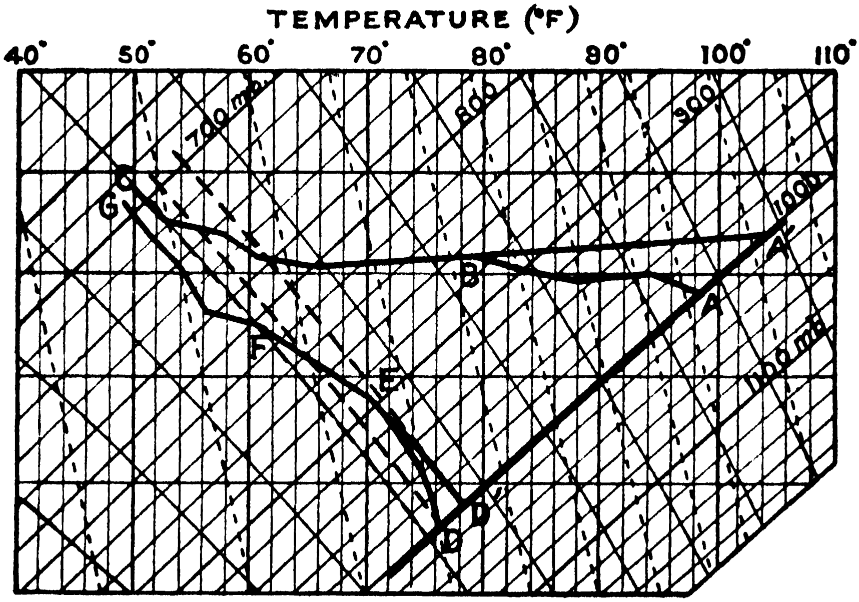

Fig. 2. Tephigram-Drigh Road. 5-10-1931
(1117 Hrs. I.S.T.)

It will appear from *Fig. 2*, that although the energy of latent instability that could be realised under suitable conditions was not large, the layer of latent instability extended from the surface up to 800 mbs. (the layer DEF), *i.e.*, it was about 2 Km. thick.

The maximum temperature rose to 105°F that afternoon and the corresponding W.B. was 78°F. The tephigram and W.B. curve at the time of the maximum would thus be approximately A'BC and D'EFG respectively (*Fig. 2*). It will appear from the tephigram that in the afternoon the superadiabatic gradients due to insolation extended right up to about 800 mbs., *i.e.*, in the whole layer of latent instability and that the amount of energy realisable from the first 100 mbs. was also somewhat more than what it was at 1100 hrs. Further the air in the first 160 mbs. could rise under the influence of insolation alone to heights where it could release its energy of latent instability. The insolation was responsible for the re-appearance of clouds after 1100 hrs. From 1300 hrs. to 1530 hrs. cumulus clouds without anvil were visible and they were gradually increasing in amount. From the autographic records it appears that the sea air arrived at Drigh Road at about 1430 hrs. ; it had however no pronounced southerly component and its depth was only about 0·5 Km. (0·5

Km. direction was 260° and above this, direction was NE up to at least 4 Km.). The incidence of sea air therefore could not aid to any appreciable extent the action of insolation in realising energy and development of thunderstorm. In the absence of any other process aiding the increase of latent instability and the supply of further trigger, one would infer that thundery conditions should occur as mentioned in the previous paper[1]. The sequence of weather given below justifies the inference.

> " At 1600 hrs. some KN appeared with thunder and slight drizzle. At 1630 hrs. some nimbus also appeared and there was intermittent drizzle. Light drizzle again started at 1700 hrs. accompanied with thunder. There was also drizzle between 1728 and 1731 hrs. After this the cloud amount gradually decreased ".

It may be of interest to mention here that the afternoon tephigram of this day was more or less similar to the tephigram of the 29th June 1936[1] *(Fig. 4)* when Drigh Road had the strongest squall of 81 m.p.h. on record; the superadiabatic gradient extended on both the days up to about 800 mbs. (*i.e.*, 2 km.) and if the tephigram alone is considered, one would expect that if a squall of 81 m.p.h. was recorded on the 29th June 1936, a full-fledged thunderstorm should have also occurred on the 5th October 1931. Yet as mentioned before, on the latter date there were only slight thundery conditions with drizzle at Karachi. The causes of this difference on the two days are not far to seek. If one considers the layer of latent instability it will appear that on the 5th October 1931, it extended up to 800 mbs. while on the 29th June 1936, it extended up to 700 mbs. thus showing that even if the degree of latent instability layer for layer was the same, yet more energy could be realised for the development of a thunderstorm on the latter than the former date. Further the sea air which as shown before, increases the degree of latent instability and also acts as a trigger or helps insolation in aiding release of energy was on the 29th June 1936, at least 1 Km. deep and had a pronounced southerly component, whereas on the 5th October 1931, it was only about 0·5 Km. deep and had no pronounced southerly component.

8. Thunderstorm of 24th March 1932.

On the 24th morning a western disturbance lay over southeast Baluchistan and the adjoining parts of middle Sind and the upper winds over Karachi were moderate W to NW at least up to 2 Km. By the next morning the disturbance lay over Sind and the adjoining parts of west Rajputana.

From the early morning the sky was half covered with stratus clouds. After 0930 hrs. the stratus began to change to K and at 1100 hrs. there was all fractocumulus possessing thundery tops. At about 1235 hrs. there appeared on the NE horizon some big cumulus clouds of great height, from the base of which rain wisps were seen and they were slowly moving towards the observatory. There was an aeroplane ascent at about 1300 hrs. just before the thunderstorm and its data are give in *Fig. 3*, ABCD and EFGHI being the D.B. and W.B. curves respectively. It may be mentioned that the maximum temperature was recorded between 1215 and 1225 hrs., *i.e.*, before the ascent.

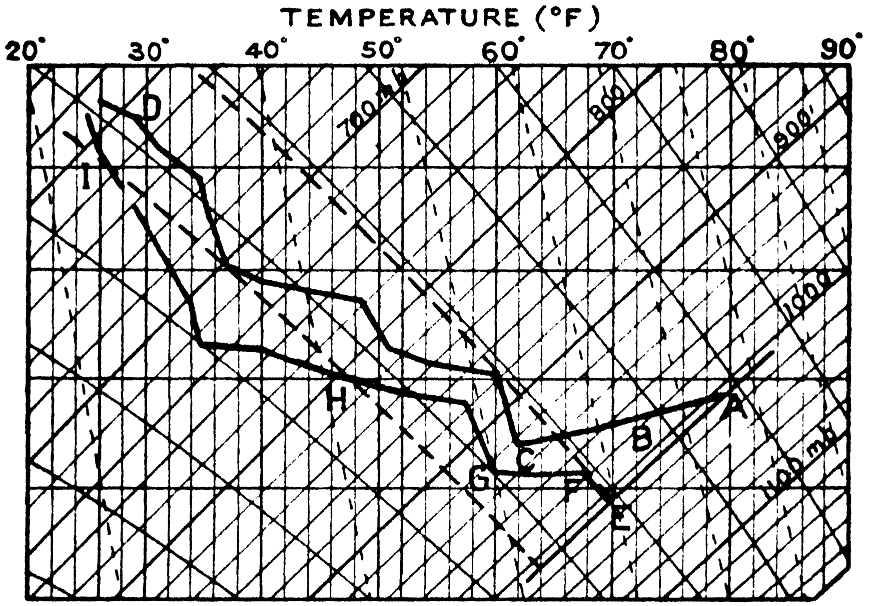

Fig. 3. Tephigram-Drigh Road. 24-3-1932.
(1300 Hrs. I.S.T.)

From *Fig. 3* it will appear that there was latent instability from the surface up to 810 mbs. The development of cumulus with thundery tops after 0930 hrs., was probably due to the ascent of the air particles in the first 50 mbs. or so as a result of insolation. But it would appear that it was not insolation alone that was responsible for the realisation of energy from the whole layer of latent instability (layer EFGH).

As seen from the autographic records the wind over the station began to change at 1314 hrs. from W to E through N and from E to SE, the force falling at the same time from 4-5 to 2-3. With this there was a fall in temperature of about 7°F. At 1317 hrs. thunder was heard towards the north. By 1320 hrs. one big cumulus base was overhead and precipitation began over the station. At 1345 hrs. with the approach of another cumulus base a thundersquall was experienced, temperature falling further by 4°F, the maximum velocity being 30 m.p.h. During the squall, clouds of dust were raised and although the visibility was 6 at the station, it must have been about 1-2 towards the south ; there was no measurable amount of rain although some drizzle had occurred. After the squall it was remarkable that while the lower clouds moved westwards, the higher ones moved eastwards. The sky began to clear after 1440 hrs. beginning with the NE horizon. During the thundersquall the D.B. had fallen and relative humidity had increasd but both these became by 1540 hrs. almost what they were before the squall. A pilot balloon ascent at 15 hrs. showed that the wind was SSE at 0·5 Km., SSW at 1 Km. and WSW at 2 Km. Another pilot balloon ascent at 1600 hrs. showed SW to W winds up to 2 Km. and W to NW winds above up to 8 Km.

The temperature and humidity changes given above when considered along with the afternoon upper wind direction up to 2 Km. will incline one to the view that the trigger for the release of the energy of latent instability giving rise to thunderstorm was not supplied by the cold air in the rear of the western disturbance mentioned above. It therefore appears that the flow of cold air from an adjoining thunderstorm acted as a trigger in the present case ; the facts mentioned above, that at about 1235 hrs. there appeared on the NE horizon some big cumulus clouds of great height and at 1317 hrs. thunder was first heard towards the north, support this conclusion.

4. Thundery conditions and duststorm of 29th March 1932.

A western disturbance lay over Sind on the 29th morning. Upper winds over Drigh Road at 0700 hrs. were W to NW at least up to 2 Km., the velocity being 47, 50 and 104 Kms./hr. at 0·5, 1·0 and 2·0 Km.

The sky was almost clear up to about 1300 hrs. Data of an aeroplane ascent made between 1230 and 1330 hrs. are given in *Fig. 4*. ABCD and EFGHI being the D.B. and W.B. curves respectively.

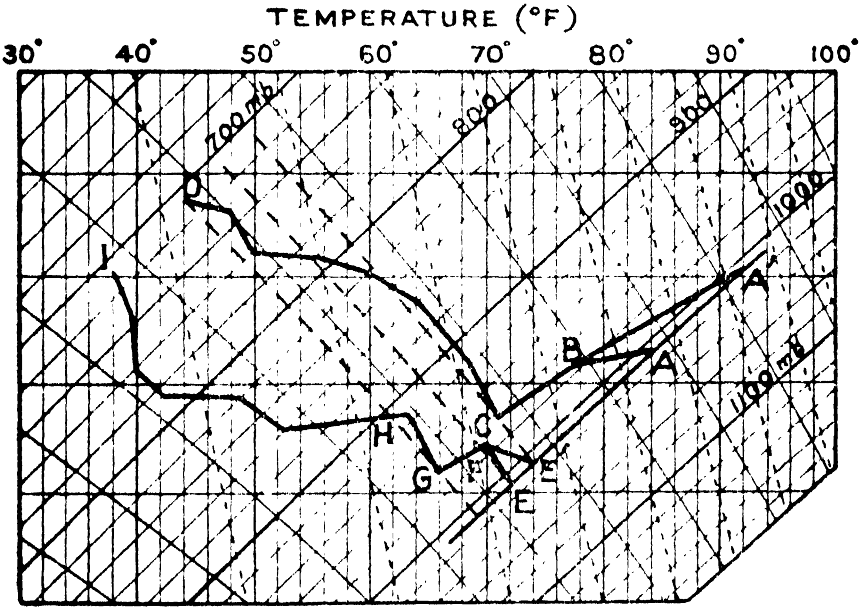

Fig. 4. Tephigram - Drigh Road . 29-3-1932
(1310 Hrs. I.S.T.)

It will appear from the figure that although the layer of latent instability extended from the surface up to about 900 mbs., the amount of energy that could be realised was only slight and that too could not be realised unless the surface particles could be raised to a height corresponding to about 800 mbs. pressure. The maximum temperature of 92·5°F occurred at about 1418 hrs. I.S.T. and the corresponding W.B. was 74°F. Thus A′BCD and E′FGHI would be the tephigram and the W.B. curve respectively at the time of the maximum. It will appear from the afternoon curves that the air in the first 40 mbs. alone could release energy of latent instability as a result of insolation ; this was responsible for some cumulus in the afternoon. Insolation could not alone therefore cause dust or thunderstorm.

The sea air came at about 1408 hrs. as seen from the anemogram, thermogram and hygrogram. It was however less than 0·5 Km. deep as judged from the 1500 hrs. pilot balloon ascent, 0·5 Km. wind being from W. The pilot balloon ascent showed mainly W. winds above the surface except at 1 Km. and 2 Km. where they were NNE and NW respectively. The sea air also could not therefore have helped the production of a thunderstorm or duststorm.

The following is a summary of weather experienced that afternoon :—

> " A bank of towering cumulus clouds of great vertical development was seen at 1510 hrs. on the NE sky. The clouds were moving slowly towards SW. In other parts of the sky there was some fracto-cumulus. Visibility at this time was 5 towards the SE and in other directions it was 7. At 1517 hrs. thunder was heard towards the NE where towering cumulus had appeared. The cumulus was later rising higher and higher and at the same time moving slowly towards the station. By 1700 hrs. these cumulus clouds were very near the station towards the NE, the amount being about 5. Duststorm of a severe kind could be seen below the towering clouds. Sometimes the dustwall extended to such a height that only tops of the towering clouds could be seen. At 1712 hrs. the wind had changed from WSW to NNW and visibility became 4 towards the NE—it being 7 towards the other sides. Gradually the duststorm approached the station and at 1723 hrs. the visibility was reduced to 2. Between 1730 and 1735 hrs. temperature fell by about 4°F (the W.B. fall during this period as judged from the hygrogram was about 8°F). The wind was all the time veering and at about 1725 hrs. when it became northerly, a squall was experienced during which the wind reached a velocity of 33 m.p.h. at 1740 hrs., the direction at 1800 hrs. having become E. During the squall visibility varied from 0 to 2. After 1740 hrs. visibility began to improve and by 1805 hrs. it was between 6 and 7 and there remained only cumulus (amount about 2) in the sky. There was no rain ".

It has been mentioned earlier that a western disturbance lay over Sind on the morning of the 29th. During the day it moved eastwards and lay over the west United Provinces on the 30th morning ; in connection with this a cold front moved across Sind and west Rajputana as is evident from the fact that on this very evening, *i.e.*, on the 29th. Hyderabad had a severe duststorm with wind of hurricane force from N at about 1630 hrs., Chhor had a duststorm with visibility 0 at 1735 hrs., Barmer had a duststorm with visibility 0 and strong northwesterly wind at 1900 hrs. followed by a thunderstorm with drizzle at 2010 hrs. and Jodhpur had during night a duststorm followed by drizzle and lightning. As mentioned in case I, *i.e.*, for the dust and thunderstorm on the 27th. November 1938, in this case also the earlier arrival of the cold air associated with the cold front, in the levels above the hills than in the lower levels and at the surface must have produced a high degree of latent instability, and later when the cold air arrived at the surface, it must have acted as a trigger for the release of the energy of latent instability and consequent development of a thunderstorm.

It may be added that the remarkable point about the tephigram on this day is the very large amount of energy due to vertical instability, *i.e.*, energy which will be realisable even by the ascent of dry air, and this must have also contributed somewhat to the development of the duststorm besides the point mentioned above. Precipitation did not occur due to the absence of enough water vapour.

5. Thunderstorm of 8th July 1932.

Between the 7th and 8th morning the monsoon had been strong along the west coast of the Peninsula and in Gujarat and light showers had also occurred at Chhor, Badin and Hyderabad in lower Sind. The upper winds at Karachi on the 8th morning were generally moderate between SW and WSW upto 1 Km. and between E and SE from 1 to 4 Km.

In Fig. 5 are given the tephigram ABCD and the W.B. curve EFGH for that morning.

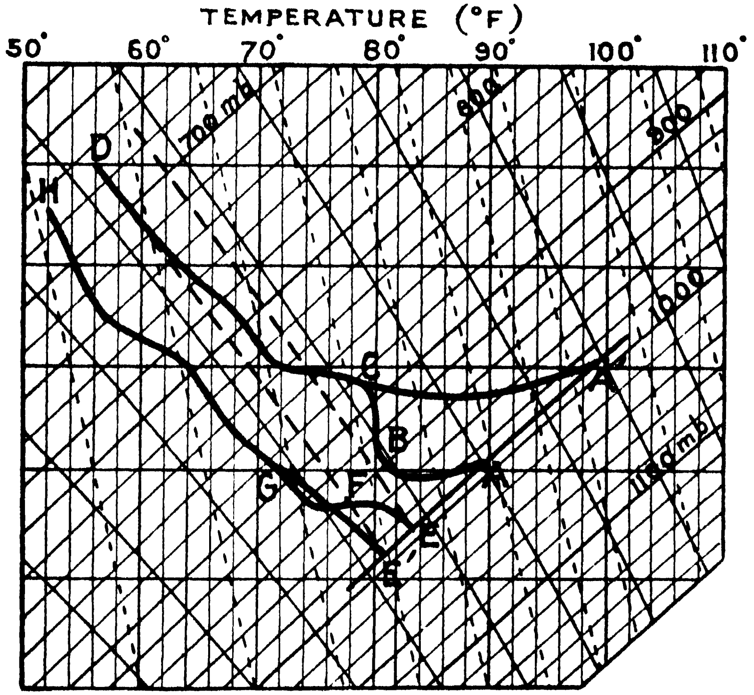

Fig. 5. Tephigram - Drigh Road. 8-7-1932
(0957 Hrs. I.S.T.)

It will appear that although the characteristic inversion[1] was not there, still there was isothermal region between 930 and 900 mbs. The layer of latent instability EF was only about 55 mbs. and would not be able to release any energy unless raised above 850 mbs. One would thus expect that a thunderstorm should not have developed over Drigh Road in ordinary course on that day. The following is an extract from the weather diary for the day in question :—

> "The sky was cloudy with high and medium clouds till about 1600 hrs. Some cumulus clouds appeared after 1300 hrs. but they disappeared after 1600 hrs. At 1750 hrs. thunder was heard at a distance towards the SE. Thunder came overhead at about 1836 hrs., when drizzle began. At about 1840 hrs. wind changed to S from WSW and suddenly

> rose to 34 m.p.h., dust being raised here and there. Rain began to pour in showers at 1842 hrs. and lasted for about 7 minutes. Light drizzle continued till 1910 hrs. From 1900 hrs. thunder and lightning were noticed towards the southwestern parts. The approach of the disturbance was heralded by thick cirro-stratus on the eastern sky at about 1700 hrs. and when thunder was overhead, there was nimbus underneath the advancing cirro-stratus with a line of fracto-cumulus hardly 200 ft. from ground level. During the disturbance the northwestern sky remained clear ".

Let us now examine why the thunderstorm occurred over Drigh Road although the tephigram and W.B. curve (*Fig. 5*) of the morning did not indicate possibility of the same as mentioned above. The maximum temperature rose to 100°F that afternoon and the corresponding W.B. was 81°F. The afternoon tephigram and W.B. curve would thus have been A′CD and E′GH respectively. It would appear that in the afternoon at the time of maximum there was practically no latent instability in any layer. From the weather diary it would also appear that only some cumulus clouds developed in the afternoon as a result of insolation and they again disappeared after 1600 hrs. From the anemogram it appears that the southwesterly sea air arrived at Drigh Road at about 2 P.M. From the afternoon upper winds it is also clear that the sea air did not extend appreciably above the surface because at 0·5 Km. the wind direction was WSW, and above it the direction was between N and E. Thus insolation as well as advent of sea breeze were not responsible for the thunderstorm on the 8th afternoon.

From the weather diary it is clear that the thunderstorm did not develop over Drigh Road itself. It has already been mentioned before that the monsoon was strong in Gujarat between the 7th and 8th and that showers in connection with the advancing monsoon current had already occurred at some stations in lower Sind on the 7th. From the weather chart for the 8th morning it is seen that the surface of discontinuity in connection with the advancing monsoon current was still persisting near about the same region as on the 7th and it is probable that latent instability was produced as a result of the spreading of the monsoon air and the movement of the discontinuity, and the discontinuity supplied the trigger for the release of energy for the development of thunderstorm.

6. Thunderstorm of 12th July 1932.

The monsoon was strong in lower Sind and Gujarat between the 11th and 12th July in connection with a well-marked trough of low pressure which had moved from the north Arabian Sea to Cutch by 0800 hrs. of the latter date. The upper winds over Karachi on the 12th morning were mainly from NNE at least up to 3 Km.

The data of aeroplane ascent on the 12th are given in *Fig. 6,* ABC and DEFG being the tephigram and W.B. curve respectively.

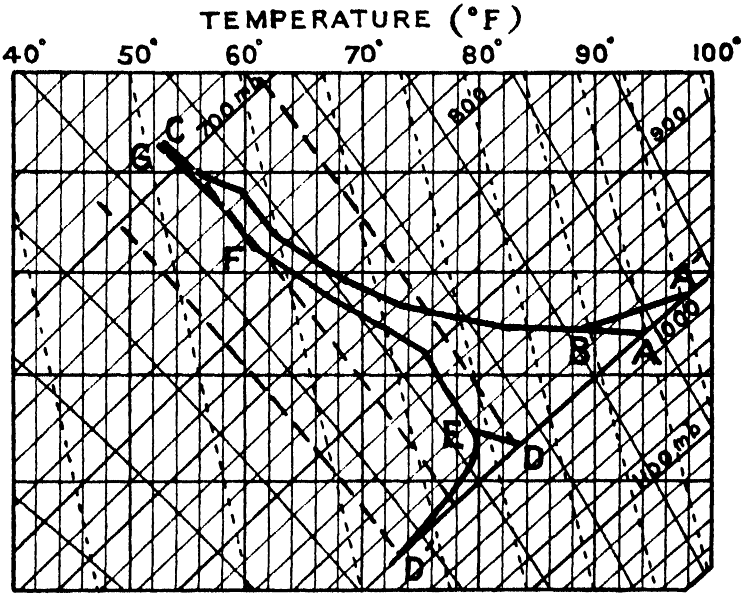

Fig. 6. Tephigram - Drigh Road. 12-7-1932 (1137 Hrs. I.S.T.)

It would appear that the characteristic inversion[1] of the monsoon months was absent and the layer of latent instability extended from the surface up to 760 mbs. (layer DEF). Conditions were thus favourable for the development of a thunderstorm over Drigh Road itself if factors like insolation, sea air and convergence of winds due to nearness of a surface of discontinuity could help realisation of the energy of latent instability as mentioned in the earlier paper[1].

The maximum temperature rose to 97°F that afternoon and the corresponding W.B. was 73°F., A'BC and D'EFG being the tephigram and W.B. curve respectively. The maximum temperature did not rise very much on the day as the sky was partly to three-fourths clouded with high, medium and low clouds since the morning. From the anemogram it appears that sea air with any pronounced southerly component did not arrive that afternoon; further the sea air did not also extend much higher up as the 1500 hrs. pilot balloon ascent showed moderate WSW wind up to 0·5 Km. and winds with marked east component above that height. It would therefore appear that insolation and sea air could not help to any large extent release of energy of latent instability and consequent development of a thunderstorm. Yet there was a thunderstorm as would appear from the following weather remarks :—

Hours I.S.T.	*Remarks.*
1210—1212	Slight drizzle.
1212—1227	Showers.
1243—1247	Showers.
1247—1250	Drizzle.
1250—1600	Intermittent showers with roar of thunder at 1316 hrs.
1756—1801	Slight drizzle.
1801—1854	Slight thunderstorm and thick intermittent drizzle.
1854—2210	Moderate thunderstorm and heavy intermittent showers.

As mentioned before there was a well-marked trough of low pressure over Cutch on the 12th Morning. In the course of the 12th the low pressure moved northwards and by the next morning it merged into and accentuated the seasonal trough of low pressure over Baluchistan. Thus the surface of discontinuity associated with the low pressure was near Drigh Road on the 12th and its approach to the station in the evening must have produced latent instability in the lower levels, thus increasing considerably the amount of energy realisable and also supplied trigger for the development of the thunderstorm.

7. Dust-raising winds of 2nd January 1932.

On this day there was fine anticyclonic weather over northwest India with light mainly northeasterly winds although a western disturbance was causing cloud along the frontier. The upper winds over Drigh Road in the morning were moderate to strong NE to E up to 1 Km., light NNW at 2 Km. and SW aloft with moderate force at 3 Km. and strong to gale force at 4, 5 and 6 Km. and remained practically unchanged during the afternoon as judged from 15 hrs. pilot balloon ascent.

The sky was clear and there was good visibility up to 0945 hrs. Thereafter the surface wind, which had force 3 at 0900 hrs. increased in force and began to blow with 18 to 20 m.p.h. and visibility began to deteriorate due to raising of dust. At 1010 hrs. visibility had become 3 and during the next 20 minutes it further decreased to 0. From 1030 hrs. to 1200 hrs. the visibility varied from 0 to 1. Thereafter the visibility improved to 2 to 3 but the wind did not abate, the wind velocity occasionally increasing to 32 m.p.h. between 1040 and 1220 hrs. The wind force then gradually decreased and visibility improved to 6 by 1400 hrs.

There was an aeroplane ascent at 1138 hrs. and its data are given in *Fig. 7*, AB and CD being the D.B. and W.B. curves respectively.

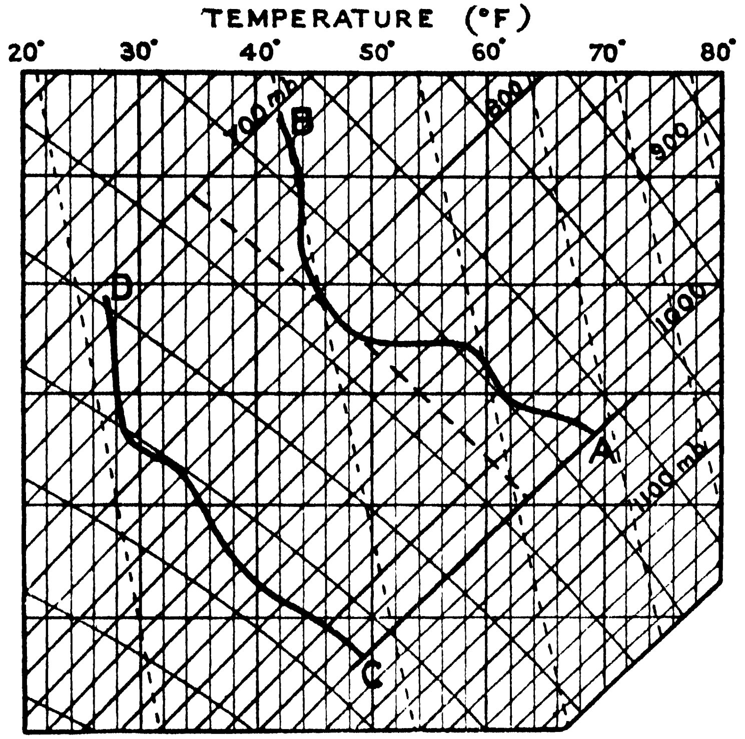

Fig. 7. Tephigram - Drigh Road. 2-1-1932.
(1138 Hrs. I.S.T.)

As dust-raising winds are not necessarily convective phenomena, one must not expect them to be associated with latent instability or vertical instability. It will be clear from the figure that there were neither superadiabatic gradients nor any latent instability in any level. There was dryness at all levels.

It may be mentioned that there are many occasions in winter when strong dust-raising winds occur at Drigh Road without there being any latent instability, the distribution of D.B. and W.B. being as given in *Fig. 7*.

8. Dust-raising winds of the 13th June 1932.

On the 13th morning there was the usual cyclonic circulation over northwest India ; the pressure gradient was strong. The upper winds over Drigh Road in the morning were strong and mainly westerly at least up to 1 Km.

The sky was half clouded with stratus (the seasonal characteristic) up to about 1000 hrs. when clouds began to disappear and there was only about 1/10th cloud at

1100 hrs. There was an aeroplane ascent at about 1100 hrs. and its data are plotted in *Fig. 8*, ABCD and EF being the D.B. and W.B. curves respectively.

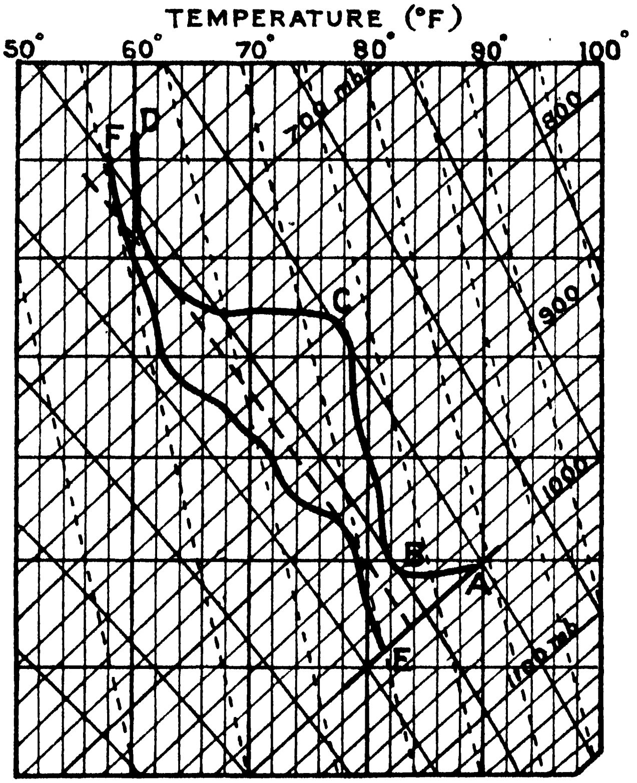

Fig. 8. Tephigram - Drigh Road. 13-6-1932
(1053 Hrs. I.S.T.)

It will appear from the figure that there was no latent instability in any layer on this day. From the tephigram and W.B. curve one would not therefore expect any abnormal weather at all on this day. Yet visibility deteriorated due to raising of dust by wind as will be seen from the weather diary given below :—

> " After 1100 hrs. wind velocity began to increase gradually causing the raising of dust and deterioration of visibility. After 1200 hrs. visibility became 5 on all sides except to the southeast and south corner where now and then visibility was 4 to 5. Later (1245 hrs.) the visibility decreased further and became 4 at 1257 hrs. The wind velocity was from 28 to 32 m.p.h. but at 1306 hrs. it rose to 36 m.p.h. for a few seconds. Visibility continued to be about 4 till about 1346 hrs. when it began to improve. After 1600 hrs. stratus clouds began to appear gradually increasing in amount and after 1700 hrs. with the fall in wind force, dust began to clear off slowly. Visibility was good at 1900 hrs. The afternoon upper winds were also strong and mainly from west at least up to 2 Km.".

The deterioration of visibility in the present instance was on account of raising of dust by strong surface winds as a result of strong pressure gradient. An examination of the aeroplane ascents on the days of dust-raising winds in summer shows that there is a strong pressure gradient but no latent instability. The tephigram and the W.B. curve for this day again show as on the 2nd January 1932, that the presence of latent instability or superadiabatic gradients is not necessary for the occurrance of dust-raising winds.

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BY

J. M. SIL.

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A HISTORICAL NOTE ON THE STANDARD FOR THE MEASUREMENT OF ATMOSPHERIC PRESSURE IN INDIA.

BY

J. M. SIL.

(*Received on 13th October 1938.*)

Abstract.—The data of atmospheric pressure in India have been based for about three quarters of a century on one and the same standard called the Calcutta Standard. The relation of this Indian Standard to the Kew standard barometer has been traced for the period, 1871 to date; the mean value of its correction with respect to the Kew is found to be −0″·009. An account of the Calcutta Standard together with the procedure adopted for its maintenance has been given. The importance of this Indian standard, which has been the basis for all pressure data collected from the whole of the Indian land and sea areas and also from the adjoining countries of Burma, Afghanistan, Iran and Arabia, has been emphasised. The history of the sub-standard barometers maintained in the India Meteorological Department has also been collected as far as possible and given in the appendix.

The Calcutta Standard.—For about three quarters of a century, the ultimate standard for the measurement of atmospheric pressure in India has been the Calcutta Standard. The basis of this standard was originally the readings of a portable standard barometer, numbered 86 by J. Newman, London. It was made on the Newman principle and had a rectangular frame and movable scale. It was supposed to be accurate and therefore no index correction was applied to its readings. The Surveyor-General of India originally obtained this instrument and kept it in his office at Calcutta, mainly to standardise surveying aneroids and other instruments for the measurement of atmospheric pressure. The exact date of installation of the barometer cannot now be traced but the records show that the instrument was being used as a standard at the time when barometric observations began to be made systematically in northern India. From meagre records it is however gathered that the standard barometer Newman No. 86 was in use prior to 1855. Apart from this portable standard there was no other instrument in the country upto 1869,* which was used as a standard for comparison of barometers.

Barometer No. 86
by
J. Newman,
London
(1855 to date).

In 1869, with the inauguration of a Meteorological Service in Bengal, four good barometers were taken by Blanford from the office of the Surveyor General, Calcutta, to be employed as secondary standards. The correction of each of these barometers was determined from time to time by direct or indirect comparisons with Newman No. 86 which gradually came to be known as the Calcutta Standard and the corrections so determined were actually applied to obtain the true pressure according to Indian convention. The pressure data at various stations collected by the Meteorological Service between 1869 and 1875, were all based on the secondary standard and therefore ultimately on the Calcutta Standard. (The Secondary standards used during this period have been listed under *Table I* at page 50).

In September 1875, the Imperial Meteorological Department was founded with its head office and observatory at Alipore, but Newman No. 86 was not transferred to the Meteorological Department until March 1877. The observatory was completed in 1876 and some time during that year two Newman barometers, numbered 109 and 112, were obtained from the Surveyor General's Office for use as secondary standards at Alipore. The Newman No. 109, before its transfer was very carefully compared with the Newman No. 86 and found to require a correction of—0″·0003. There is, however, no record of a direct comparison of Newman No. 112 with the Calcutta Standard.

Towards the end of March 1877, Newman No. 86 (the Calcutta Standard itself) was removed from the Surveyor General's Office and installed in the Alipore Observatory. Shortly after its removal, the instrument developed a leak and air entered the tube (*vide* Ind. Met. Memoir Vol. I, p. 171). In the latter part of 1877 the instrument had to be dismantled for repairs and during the next 18 years attempts were made from time to time to set it right, but its performance was never found sufficiently satisfactory for its re-establishment as the primary standard. From 1895, however, it was satisfactory enough to be used as a secondary standard at Calcutta and from 1928, at Poona. The correction of No. 86 changed, of course, in 1877 and the problem then was— how is the initial standard, the Calcutta Standard of Newman No. 86 as it originally existed, to be maintained ? This maintenance of standard was actually achieved with the help of two good barometers which had been carefully compared with Newman No. 86 in the years before 1877 ; these were the Newman portable standard barometers numbered 109 and 112 already mentioned. In constructional details they were similar to Newman No. 86. Both were well known for their reliability and accuracy. Each was used as the standard in turn with an appropriate correction applied to reduce its readings to the original Calcutta Standard.

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*At that time the Meteorological Reporter, Western India, had also a standard at Bombay but later it became a secondary to the Calcutta Standard.

It was necessary to clean or repair one or other of the standards periodically. Every time a barometer was cleaned or repaired, there was a great risk of its correction being changed, and, as these were not absolute standards, the change of correction could only be determined by comparison with a third barometer before and after the change. If the change produced by cleaning the barometer is accurately determined each time, the continuity of the series may be obtained by applying the original correction throughout, increased or decreased by the proper amount after each cleaning or repair. (*See Appendix.*)

The procedure adopted is given below :—

(*a*) Newman No. 109, which had been carefully compared with the original Newman No. 86 and found to have a correction of —0″·0003, was adopted as the ‘ primary ’* standard with index correction as 0″·000.

(*b*) Two good barometers, Newman Nos. 112 and 94 (later on two more were added) were set up by the side of Newman No. 109 and adopted as subsidiary standards with their respective corrections to the original Newman No. 86.

(*c*) The ‘ primary ’ as well as subsidiary standards were maintained independently and their original corrections to the Calcutta Standard were never changed unless several inter-comparisons,—sometimes spreading over years— showed unmistakably a change. When any of these barometers had to be cleaned or repaired, several comparisons both before and after each cleaning or repair were carefully made and the results of all these comparisons were considered to determine the exact amount of the change in its correction.

(*d*) Each sub-standard was compared with the ‘ primary ’ once a year till 1896 and every six months thereafter. From these comparative observations the true correction of the sub-standard with respect to the ‘ primary ’ was deduced.

On this basis the original standard for the measurement of atmospheric pressure in India has been maintained from September 1877 to date.

The history of the Calcutta Standard spreads therefore over two broad periods : the period when the Newman No. 86 was existing in its original form, and the period when the standard of the original Newman No. 86 was reproduced with the help of a ‘ primary ’ standard ; the demarcation line of the two periods being September 1877, when the Newman No. 86 ceased to be used as the Calcutta Standard.

1869 to 1875. Secondary Standards.—During the first seven years of systematic meteorological work in northern India, the pressure data that were collected were from instruments that had been calibrated against the one or other of the four secondary standards at the Office of the Meteorological Reporter to the Government of Bengal which were compared from time to time with Newman No. 86, then at the Surveyor General's Office, Calcutta. They are shown in chronological order in *Table I.*

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*Hereafter the word primary with inverted commas will be used to distinguish the barometer selected for representing the Calcutta Standard, although the selected barometer is really a secondary instrument.

TABLE I.

Period.	Secondary Standard.	Corrn. to Cal. Std. as used.	Corrn. to Cal. Std. as now found.
March 1869 to August 1869	Newman No. 94	+0″ ·022	+0″ ·025
October 1869 to January 1871	,, ,,	+ ·034	+ ·025
January 1871 to August 1871	,, ,,	+ ·024	+ ·025
September 1871 to November 1871	,, ,,	+ ·025	+ ·025
December 1871 to October 1873	Casella No. 636	+ ·006	+ ·008
November 1873 to December 1873	Adie 8/1869	+ ·005	+ ·006
January 1874 to April 1874	Newman No. 94	+ ·025	+ ·025
April 1874 to April 1875	Casella No. 714	+ ·006	+ ·006
May 1875 to June 1875	Adie 8/1869	+ ·015	+ ·006
July 1875 to November 1875	Casella No. 636	+ ·008	+ ·008

In the penultimate column of *Table* I are given the values of corrections which were employed to the readings of the barometer under reference so as to obtain the 'true' atmospheric pressure. A comparison of this column with the last one would show that except for the two periods, October 1869 to January 1871 and May 1875 to June 1875, the corrections used for the secondaries were sufficiently accurate to reduce their readings to the standard of Newman No. 86. It may be remarked that the corrections to the Calcutta Standard in the last column have been based on all evidence now available ; at the time when these barometers were in use, all the evidence had not been obtained so that we find corrections were used which differ slightly from those now found.

1877 to date. 'Primary' Standards—From 1877 onwards only two barometers were used in turn to reproduce the standard of the original Newman No. 86. In *Table II* their corrections and periods of service are given.

TABLE II.

'Primary' standards.	No. 109.		No. 112.	
Period. 1	Correction to Calcutta Standard as used. 2	Correction to Calcutta Standard as now found. 3	Correction to Calcutta Standard as used. 4	Correction to Calcutta Standard as now found. 5
September 1877 to August 1879	0″·000	0″·000	..	..
August 1879 to October 1879	..	..	—0″·003	—0″·003
November 1879 to April 1880	0″·000	—0″·008	..	..
April 1880 to May 1890	—0″·005	—0″·008	..	..
May 1890 to November 1890	..	..	—0″·003	—0″·003
December 1890 to October 1899	+0″·005	+0″·005	..	..
October 1899 to February 1902	+0″·007	+0″·007	..	..
February 1902 to May 1902	..	..	—0″·003	—0″·003
May 1902 to October 1909	+0″·006	+0″·006	..	..
October 1909 to January 1912	..	..	+0″·004	+0″·004
January 1912 to October 1913	..	..	+0″·004	+0″·005
October 1913 to October 1913	+0″·006	+0″·006	..	..
November 1913 to December 1916	..	..	+0″·004	+0″·005
January 1917 to date	..	..	+0″·005	+0″·005

Newman No. 109 was maintained as the 'primary' standard till October 1909 except for short intervals as indicated in the above table. In August 1879, it was accidentally damaged but was re-instated in November of that year after necessary repairs at the Mathematical Instrument Office, Calcutta. Eight sets of comparisons with No. 112 after the repairs—one in 1879 and the rest between 1882 and 1886—showed that its correction had changed from 0″·000 to −0″·008. The corrections of the barometer, that were actually used, however, were 0″·000 till April 1880 and then −0″·005 till May 1890. In the year 1890, we find that No. 112 was brought into use as the 'primary' standard for a short period, when No. 109 was sent to M. I. O. to have its tube re-filled. The barometer No. 109, which changed its correction to +0″·005 after refilling, was re-installed in December 1890 and continued as the 'primary' standard till October 1909 but during the period it was twice cleaned by M. I. O.—once in July 1899 and then in February 1902—as a result of which the correction was changed to +0″·007 in 1899 and then to +0″·006 in 1902. During the short period February to May 1902 Newman No. 112 was employed as the 'primary' standard.

In October 1909, Newman No. 112 was adopted as the 'primary' standard: careful comparison with No. 109 in August 1879 showed that it then had a correction of −0″·003 to the Calcutta Standard. No. 112 was, however, cleaned thrice by M. I. O. and the position of its fiducial point was altered in January 1906, with the results that its correction changed to +0″·004. In January 1912, it was cleaned by Mr. Field, but comparison before and after the operation did not show any change in its correction. In October 1913 it was sent to M. I. O. for repairs to the screw that adjusts its scale; the repair was completed in the same month and no change in its correction resulted; during this short period the Newman No. 109 was employed as the 'primary' standard with a correction of +0″·006.

Newman No. 112 was re-installed in November 1913 with a correction of +0″·004. Results of subsequent comparisons, however, indicated that the correction used for the barometer was slightly inadequate. A correction of +0″·005 was, therefore, introduced in January 1917. This correction is being maintained to date although the barometer was cleaned in May 1928.

Comparisons of the figures in columns 2 and 3 and of those in columns 4 and 5 of *Table II* show that the corrections actually used to correct the two barometers to the Calcutta Standard have been sufficiently accurate throughout the period except at the commencement in the case of No. 109. It is thus evident that since March 1869 all pressure data collected for meteorological work in India are ultimately based on the readings of Newman No. 86, the Calcutta Standard.

On corrections of the standards.—As has been mentioned above, after Newman No. 86 was spoiled, a few standard barometers that had been compared with it were set up and their readings were so corrected as to reproduce the Calcutta Standard. We will now proceed to examine as to how far the corrections of these standards have been appropriate. Assuming that the correction of each barometer to the Calcutta Standard has been true, the difference of the corrections of any two barometers should be just the correction of one barometer in respect of the other. Let us call this difference the 'calculated' correction. On the other hand, the actual correction of one barometer in respect of the other may be determined from comparative observations; if this value be termed as 'observed' correction, then the 'calculated' and 'observed' corrections of a barometer should satisfactorily agree with each other. This test will bring out the progressive change, if any, in any of the barometers. With this object in view *Tables III* to *VI* have been prepared.

In *Table III* dates of comparisons are shown in column 1; the corrections of No. 109 to the Calcutta Standard are given in Column 2, similar corrections of No. 112 are entered in column 3. These corrections are the original corrections of the barometer increased or decreased by the amount of change found after each cleaning or repair. For the series maintained in this way the tabular statements given in the Appendix may be seen. Column 4 contains the difference between column 3 and column 2 and therefore gives the correction of No. 112 to No. 109, assuming the correction of each to the Calcutta Standard to be correct. Column 5 contains the correction of No. 112 to No. 109 actually found from comparative observations; the mean of these 'observed corrections' over each period during which the barometer remained undisturbed has been worked out and given in column 6. In *Fig. 1*, on page 56 the values of column 5 have been plotted; the dotted and the continuous curves have been obtained using the values of columns 4 and 6 respectively.

Tables IV, *V* and *VI* give similar data for the barometers Nos. 86, 94 and 712 respectively, and *Fig. 2* on page 56 shows similar curves in respect of the barometer No. 86.

The dotted and the continuous curves in *Fig. 1* show respectively the mean 'observed' correction and the 'calculated' correction of the barometer No. 112 to No. 109. During the period 1879 to 1930—it may be observed—the 'calculated' correction agrees closely with the mean correction of the barometer as determined from a number of comparative observations: in fact, for No. 112 the maximum difference is about 0″·001 which is negligible. It may also be pointed out that the departure from the mean of any individual 'observed' correction is never more than 0″·003.

Comparisons of columns 4 and 6 of *Tables IV*, *V* and *VI* will show that the above remarks apply equally well to the other barometers, *viz.*, Nos. 86, 94 and 712. This is further illustrated in the case of No. 86 by *Fig. 2* on page 56.

This indicates that there has been no progressive change in any of the barometers; or, that all the five barometers have changed by the same amount and in the same direction—a very unlikely coincidence. Then, all the changes in a barometer have been fully accounted for by the changes that were incorporated each time the barometer was cleaned or repaired. It may, therefore, be concluded that the corrections that have been in use for any of these barometers are appropriate and would be the same as that found by comparison with Newman No. 86 had this been present in its original form today.

TABLE III.

Comparisons of corrections of Newman barometers Nos. 112 and 109.

1	2	3	4	5	6
Date.	Corrn. 109.	Corrn. 112.	112—109 (Cal.).	112—109 (Obs.)	Mean Obs.
	″	″	″	″	″
Aug. 1879 ..	000	—·003	—·003	—·003	+·0051
Nov. 1879 ..	—·008	—·003	+·005	+·002	
Nov. 1880 ..	,,	,,	,,	,,	
Nov. 1881 ..	,,	,,	,,	,,	
July 1882 ..	,,	,,	,,	+·004	
Jan. 1883 ..	,,	,,	,,	+·005	
June 1884 ..	,,	,,	,,	,,	
September 1884	,,	,,	,,	,,	
February 1885	,,	,,	,,	,,	
September 1885	,,	,,	,,	+·006	
March 1886 ..	,,	,,	,,	+·007	
October 1886 ..	,,	,,	,,	+·006	
April 1887 ..	,,	,,	,,	,,	
November 1887	,,	,,	,,	+·007	
May 1888 ..	,,	,,	,,	,,	
November 1888	,,	,,	,,	,,	
May 1889 ..	,,	,,	,,	+·005	
November 1889	,,	,,	,,	+·007	
February 1890	,,	,,	,,	+·005	
March 1890 ..	,,	,,	,,	+·004	
November 1890	+·005	—·003	—·008	—·006	—·0066
January 1891 ..	,,	,,	,,	—·007	
February 1892	,,	,,	,,	—·008	
September 1892	,,	,,	,,	—·005	
November 1892	,,	,,	,,	,,	
July 1893 ..	,,	,,	,,	—·007	
February 1894	,,	,,	,,	,,	
December 1894	,,	,,	,,	—·006	
June 1895 ..	,,	,,	,,	—·007	
November 1895	,,	,,	,,	—·007	
January 1896 ..	,,	,,	,,	,,	
October 1896 ..	,,	,,	,,	,,	
September 1897				,,	
January 1898 ..	,,	,,	,,	,,	
November 1898	,,	,,	,,	,,	
June 1899 ..	,,	,,	,,	—·006	
July 1899 ..	,,	,,	,,	—·007	
October 1899 ..	+·007	,,	—·010	—·010	—·0092
May 1900 ..	,,	,,	,,	—·009	
September 1900	,,	,,	,,	—·011	
May 1901 ..	,,	,,	,,	—·008	
September 1901	,,	,,	,,	,,	
January 1902 ..	,,	,,	,,	—·009	
May 1902 ..	+·006	—·005	—·009	—·008	—·0084
April 1903 ..	,,	,,	,,	—·009	
September 1903	,,	,,	,,	—·008	
April 1904 ..	,,	,,	,,	,,	
November 1904	,,	,,	,,	—·009	
May 1905 ..	,,	,,	,,	,,	
December 1905	,,	,,	,,	—·008	
September 1906	+·006	+·008	+·002	+·001	+·0022
October 1906 ..	,,	,,	,,	+·003	
December 1906	,,	,,	,,	—	
July 1907 ..	,,	,,	,,	+·001	
August 1907 ..	,,	,,	,,	+·003	
January 1908 ..	,,	,,	,,	,,	
March 1908 ..	,,	,,	,,	,,	
April 1908 ..	+·006	+·004	—·002	000	—·0015
July 1908 ..	,,	,,	,,	—	
July 1908 ..	,,	,,	,,	—·001	
January 1909 ..	,,	,,	,,	,,	
July 1909 ..	,,	,,	,,	—·002	
January 1910 ..	,,	,,	,,	—·001	
August 1910 ..	,,	,,	,,	—·002	
January 1911 ..	,,	,,	,,	,,	
August 1911 ..	,,	,,	,,	,,	
November 1911	,,	,,	,,	,,	
January 1912 ..	,,	,,	,,	,,	
January 1912 ..	+·006	+·005	—·001	·000	—·0010
June 1912 ..	,,	,,	,,	—·002	
August 1912 ..	,,	,,	,,	—·001	
January 1913 ..	,,	,,	,,	000	
July 1913 ..	,,	,,	,,	—·001	
April 1914 ..	,,	,,	,,	,,	
August 1914 ..	,,	,,	,,	,,	
March 1915 ..	,,	,,	,,	—·002	
November 1915	,,	,,	,,	000	
July 1916 ..	,,	,,	,,	—·001	
January 1917 ..	,,	,,	,,	—·002	
June 1917 ..	,,	,,	,,	,,	
February 1918 ..	,,	,,	,,	—·001	
January 1919 ..	,,	,,	,,	,,	
July 1919 ..	,,	,,	,,	000	
August 1919 ..	,,	,,	,,	,,	
January 1920 ..	,,	,,	,,	—·002	
August 1920 ..	,,	,,	,,	—·001	
January 1921 ..	,,	,,	,,	,,	
August 1921 ..	,,	,,	,,	,,	
March 1922 ..	,,	,,	,,	,,	
August 1922 ..	,,	,,	,,	,,	
August 1924 ..	,,	,,	,,	,,	
January 1925 ..	,,	,,	,,	,,	
July 1925 ..	,,	,,	,,	,,	
December 1925 ..	,,	,,	,,	—·003	
June 1926 ..	,,	,,	,,	—·002	
November 1926	,,	,,	,,	—·001	
August 1927 ..	+·004	+·005	+·001	+·003	+·0010
February 1928 ..	,,	,,	,,	+·001	
May 1928 ..	,,	,,	,,	000	
January 1929 ..	,,	,,	,,	+·001	
June 1929 ..	,,	,,	,,	000	
December 1929 ..	,,	,,	,,	+·001	
July 1930 ..	,,	,,	,,	,,	
December 1930 ..	,,	,,	,,	,,	

TABLE IV.

Comparisons of corrections of Newman barometers Nos. 86 and 109.

1	2	3	4	5	6
Date.	Corrn. 109.	Corrn. 86	86—109 (Cal.).	86—109 (Obs.)	Mean Obs.
	″	″	″	″	″
Nov. 1895 ..	+ ·005	—·007	—·012	—·012	—·0115
January 1896 ..	,,	,,	,,	—·012	
October 1896 ..	,,	,,	,,	—·013	
September 1897 ..	,,	,,	,,	—·010	
January 1898 ..	,,	,,	,,	—·012	
November 1898 ..	,,	,,	,,	,,	
June 1899 ..	,,	,,	,,	—·009	
July 1899 ..	,,	,,	,,	—·012	
October 1899 ..	+ ·007	,,	—·014	—·014	—·0135
May 1900 ..	,,	,,	,,	,,	
September 1900 ..	,,	,,	,,	—·015	
May 1901 ..	,,	,,	,,	—·013	
September 1901	,,	,,	,,	,,	
January 1902 ..	,,	,,	,,	—·012	
May 1902 ..	+ ·006	,,	—·013	—·012	—·0131
April 1903 ..	,,	,,	,,	—·013	
September 1903 ..	,,	,,	,,	—·012	
April 1904 ..	+ ·006	—·007	—·012	—·013	
November 1904 ..	,,	,,	,,	—·012	
May 1905 ..	,,	,,	,,	—·013	
December 1905 ..	,,	,,	,,	—·010	
September 1906 ..	,,	,,	,,	—·014	
October 1906 ..	,,	,,	,,	,,	
December 1906 ..	,,	,,	,,	—·012	
July 1907 ..	,,	,,	,,	—·018	
August 1907 ..	,,	,,	,,	—·016	
January 1908 ..	,,	,,	,,	—·012	
March 1908 ..	,,	,,	,,	—	
April 1908 ..	,,	—·011	—·017	—·019	
July 1908 ..	,,	,,	,,	—	
July 1908 ..	,,	,,	,,	—·019	
January 1909 ..	,,	,,	,,	—·016	
July 1909 ..	,,	,,	,,	—·020	
January 1910 ..	,,	,,	,,	—·017	
August 1910 ..	+ ·006	—·011	—·017	—·017	—·0177
January 1911 ..	,,	,,	,,	,,	
August 1911 ..	,,	,,	,,	—·020	
November 1911 ..	,,	,,	,,	—	
January 1912 ..	,,	,,	,,	—·017	
January 1912 ..	,,	,,	,,	—·016	
June 1912 ..	,,	,,	,,	—·019	
August 1912 ..	,,		,,	—·017	
January 1913 ..	,,	,,	,,	—·016	
July 1913 ..	,,	,,	,,	—·019	
April 1914 ..	,,	,,	,,	—·016	
August 1914 ..	,,	,,	,,	—·019	
March 1915 ..	,,	,,	,,	—·018	
November 1915	,,	,,	,,	,,	
July 1916 ..	,,	,,	,,	—·019	
January 1917 ..	,,	,,	,,	—·017	
June 1917 ..	,,	,,	,,	—·019	
February 1918 ..	,,	,,	,,	—·017	
January 1919 ..	,,	,,	,,	—·010	
July 1919 ..	,,	,,	,,	—·018	
August 1919 ..	,,	,,	,,	—·017	
January 1920 ..	,,	,,	,,	—·018	
August 1920 ..	,,	,,	,,	,,	
January 1921 ..	,,	,,	,,	—·017	
August 1921 ..	,,	,,	,,	—·019	
March 1922 ..	,,	,,	,,	—·018	
August 1922 ..	,,	,,	,,	,,	
August 1924 ..	,,	,,	,,	—·017	
January 1925 ..	,,	,,	,,	—·018	
July 1925 ..	,,	,,	,,	—·017	
December 1925 ..	,,	,,	,,	,,	
June 1926 ..	,,	,,	,,	—·019	
November 1926 ..	,,	,,	,,	—·016	
August 1927 ..	+ 0·44	—·011	—·015	—·018	—·0170
February 1928 ..	,,	,,	,,	—·016	

TABLE V.

Comparisons of corrections of Newman barometers Nos. 94 and 109.

1	2	3	4	5	6
Date.	Corrn. 109.	Corrn. 94.	94—109 (Cal.).	94—109 (Obs.)	Mean Obs.
	″	″	″	″	″
April 1904 ..	+·006	+·016	+·010	+·008	+·010
November 1904 ..	,,	,,	,,	+·012	
May 1905 ..	,,	,,	,,	+·011	
December 1905 ..	,,	,,	,,	+·012	
September 1906 ..	,,	,,	,,	+·009	
October 1906 ..	,,	,,	,,	,,	
December 1906 ..	,,	,,	,,	+·010	
July 1907 ..	,,	,,	,,	+·008	
August 1907 ..	,,	,,	,,	+·009	
January 1908 ..	,,	,,	,,	+·012	
March 1908 ..	,,	,,	,,	—	
April 1908 ..	+.006	+·017	+·011	+·011	
July 1908 ..	,,	,,	,,	,,	
July 1908 ..	,,	,,	,,	,,	
January 1909 ..	,,	,,	,,	+·010	
July 1909 ..	,,	,,	,,	+·009	
January 1910 ..	,,	,,	,,	+·011	

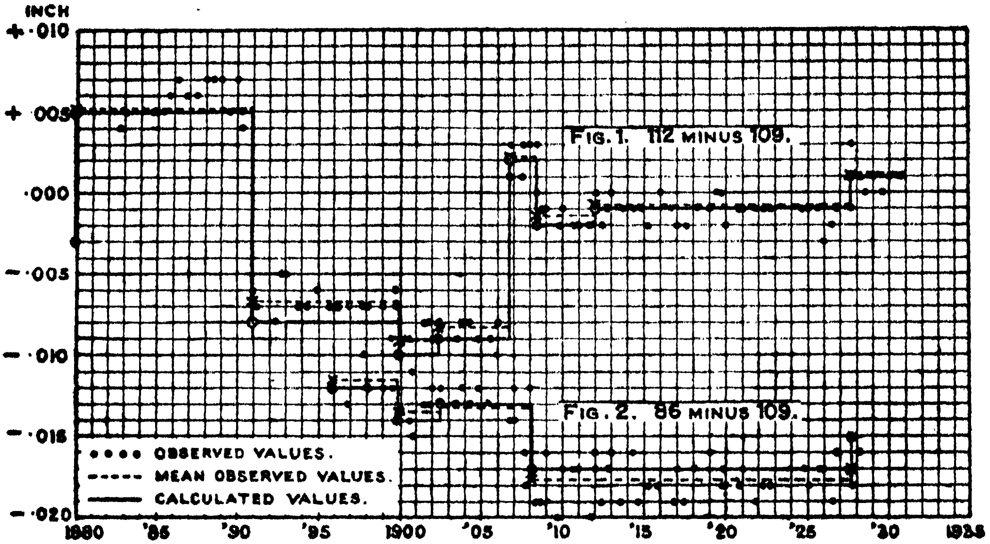
1	2	3	4	5	6
Date.	Corrn. 109.	Corrn. 94	94—109 (Cal.).	94—109 (Obs.)	Mean Obs.
	″	″	″	″	″
August 1910 ..	+.006	+·017	+·011	+·011	+·0105
January 1911 ..	,,	,,	,,	+·010	
August 1911 ..	,,	,,	,,	,,	
November 1911 ..	,,	,,	,,	—	
January 1912 ..	,,	,,	,,	+·010	
January 1912 ..	,,	,,	,,	+·012	
June 1912 ..	,,	,,	,,	+·010	
August 1912 ..	,,	,,	,,	+·013	
January 1913 ..	,,	,,	,,	+·012	
July 1913 ..	,,	,,	,,	+·009	
April 1914 ..	,,	,,	,,	+·012	
August 1914 ..	+·006	+·016	+·011	+·010	
March 1915 ..	,,	,,	,,	,,	
November 1915 ..	,,	,,	,,	,,	
July 1916 ..	,,	,,	,,	+·009	
January 1917 ..	,,	,,	,,	+·010	
June 1917 ..	,,	,,	,,	,,	
February 1918 ..	,,	,,	,,	,,	

TABLE VI.

Comparisons of corrections of Newman barometers Nos. 712 and 109.

1	2	3	4	5	6
Date.	Corrn. 109.	Corrn. 712.	712—109 (Cal.).	712—109 (Obs.)	Mean Obs.
	″	″	″	″	″
March 1908 ..	+.006	+·015	+·009	+·006	+·0084
April 1908 ..	,,	,,	,,	—	
July 1908 ..	,,	,,	,,	+·003	
July 1908 ..	,,	,,	,,	—	
January 1909 ..	,,	,,	,,	+·005	
July 1909 ..	,,	,,	,,	+·004	
January 1910 ..	,,	,,	,,	+·005	
August 1910 ..	,,	,,	,,	+·011	
January 1911 ..	,,	,,	,,	+·010	
August 1911 ..	,,	,,	,,	+·008	
November 1911 ..	,,	,,	,,	—	
January 1912 ..	,,	,,	,,	—	
January 1912 ..	,,	,,	,,	+·011	
June 1912 ..	,,	,,	,,	—	
August 1912 ..	,,	,,	,,	+·011	
January 1913 ..	,,	,,	,,	+·012	
July 1913 ..	,,	,,	,,	+·008	
April 1914 ..	,,	,,	,,	+·011	
August 1914 ..	,,	,,	,,	+·009	
March 1915 ..	,,	,,	,,	+·007	
November 1915 ..	,,	,,	,,	+·008	

1	2	3	4	5	6
Date.	Corrn. 109.	Corrn. 712.	712—109 (Cal.).	712—109 (Obs.)	Mean Obs.
	″	″	″	″	″
July 1916 ..	+·006	+·015	+·009	+·008	
January 1917 ..	,,	,,	,,	+·010	
June 1917 ..	,,	,,	,,	+·008	
February 1918 ..	,,	,,	,,	+·010	
January 1919 ..	,,	,,	,,	+·008	
July 1919 ..	,,	,,	,,	+·009	
August 1919 ..	,,	,,	,,	+·008	
January 1920 ..	,,	,,	,,	+·011	
August 1920 ..	,,	+·013	+·007	+·006	+·0067
January 1921 ..	,,	,,	,,	+·007	
August 1921 ..	,,	,,	,,	+·005	
March 1922 ..	,,	,,	,,	+·008	
August 1922 ..	,,	,,	,,	+·006	
August 1924 ..	,,	,,	,,	+·008	
January 1925 ..	,,	,,	,,	,,	
July 1925 ..	,,	,,	,,	+·007	
December 1925 ..	,,	,,	,,	+·006	
June 1926 ..	,,	,,	,,	,,	
November 1926 ..	,,	,,	,,	+·007	
August 1927 ..	+·004	+·010	+·006	+·006	+·0063
February 1928 ..	,,	,,	,,	+·007	
May 1928 ..	,,	,,	,,	+·006	



COMPARISONS OF BAROMETERS No 112 AND 86 WITH NEWMAN BAROMETER No 109.

Kew Corrections of the 'Calcutta Standard'.

The first attempt to determine the correction of the Calcutta Standard with respect to the Kew Standard was made by Blanford[1] in 1871 when 8 Fortin barometers by Casella were received after being compared with the standard at the India Stores Department, London, whose corrections to Kew and Greenwich standards were known. They were compared at Calcutta with the secondary standard, Newman No. 94. Applying the correction of Newman No. 94 to the 'Calcutta Standard', Kew *minus* Calcutta Standard, or, △ , was found to be —0″·0109.

In July 1876, Chambers[2] compared two mountain barometers by N. & Z. numbered 705 and 711, with Newman No. 58, the standard barometer at Colaba Observatory. As the corrections of N. & Z. barometers to the Kew standard were known, the Newman No. 58 was found to have a correction of +0″·004 to Kew. Applying the then accepted correction of Newman No. 58 to the Calcutta Standard, △ works out to be —0″·008.

Attempts were also made to determine the Kew correction of the Calcutta Standard through barometers, which were provided with Kew correction certificate and were compared with the 'primary' standard at Calcutta on their arrival. It is found that 43 barometers so received during the period of October 1909 to June 1925 indicated an average value of △ as —0″·009.

Since 1933 barometers are being obtained with test certificates of the N. P. L., Teddington, giving corrections at different points of the scale. Results of comparisons of barometers, using the Poona standard as medium show the following average values :—

△ = —0″·010, through 14 barometers received in 1933 ;
△ = —0″·009, through 14 barometers received in 1934 ;
△ = —0″·009, through 8 barometers received in 1935.

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[1] Proc. Asiat. Soc. Beng. Vol. XL, part II, 1871. In this paper the number of the standard barometer at the Surveyor General's Office is incorrectly given as 84.

[2] C. Chambers, Magn. and Metl. Obsns. Bombay, 1871—1878, Introduction p. ix.

The writer undertook a comparison in 1935, with 6 Fortin barometers by Casella provided with optical arrangements for the accurate setting of the fiducial points. These barometers were certified by the N. P. L., Teddington, and transported under the personal charge of a ship captain. Inter-comparisons of these barometers in India showed that they were maintaining their mutual differences as found in England; as all the six could not possibly change their corrections equally at the same time, it was assumed that the barometers retained their respective Kew corrections after reaching Poona. Four of these were carried to Calcutta with all possible precautions and the mean of 222 observations taken during rising, falling and steady pressure with Newman No. 112 indicated a mean value of △ as —0″·0094, the value determined by each of the 4 barometers ranging between —0″·009 and —0″·010.

The results of all the comparisons are tabulated below :—

TABLE VII.

Year.	1871.	1876.	1909 to 1925.	1933.	1934.	1935.	Mean.
△	—0″·011	—0″·008	—0″·009	—0″·010	—0″·009	—0″·009	—0″·009

It may be stated that many of the certified barometers used in these comparisons were transported under special stowage from England to India and under the personal supervision of ship's officers. It is, however, doubtful whether the result of a single comparison specially carried out would have greater reliability than those obtained through the excellent series of statistical data extending over a long period. The various comparisons made since 1871 undoubtedly give satisfactorily consistent results on the assumption that the Kew Standard has maintained its correction. It may be observed that the mean value of △ as obtained from the results of all comparisons is —0″·009 and that the result of an individual comparison lies within ±0″·002 from the mean. After the comparison of 1871 the value of △ was published in the departmental publication as —0″·011 and this value has continued to be published without change, because, after all the arduous work undertaken from time to time during the last sixty-five years, the value of △ found at any time showed a difference which was not more than errors of observation.

The great importance of the Calcutta Standard can be easily judged from the fact that about 350 observatories scattered over the vast land area—from Bushire to Victoria Point in one direction and Leh to Cape Comorin in the other—are using barometers which were standardised with respect to the Calcutta Standard. Again, all pressure data collected from coastal ships plying in the Arabian Sea and the Bay of Bengal are based on the same Indian Standard. It is thus a matter of satisfaction to note that one and the same ultimate standard has been used for the measurement of atmospheric pressure not only over the whole of the Indian land and sea areas but also in the adjoining countries of Burma, Afghanistan, Iran and Arabia.

The Sub-standard barometer at Bombay.

The history of the standard barometer in India would hardly be complete without an account of Newman No. 58, the oldest barometer now in the department. This instrument is identical in design with other Newman Standard barometers, which were used in the Meteorological Service in Bengal. It was installed in 1841 at the Colaba Observatory, Bombay. When a provincial meteorological organisation was founded in western India, this barometer was mainly used to standardise the mercurial and aneroid barometers belonging to ships on the west coast. The remarkable point about this Newman No. 58 is that it has been used every day since 1841 and during the period of one complete century it has never* been dismantled for cleaning or repairs. When the mercury in the cistern formed a scum on the surface and the accurate setting of the scale became difficult, the scale of the barometer was once for all adjusted[1] in May 1866, so that the instrument could be used with suitable corrections as a Kew pattern barometer ' for the measurement of variations of atmospheric pressure '. The performance of this instrument was frequently compared with that of another Newman No. 48 which had been at the observatory since 1846. Its correction to the Kew Standard was first determined[2] in 1876 and found to be +0″·004. Another comparison with the Kew Standard was recently made in 1935 with the help of 6 Fortin barometers by Casella which were specially obtained for determining the Kew correction of the Calcutta Standard. The result indicated a correction of 0″·001. The barometer has also been compared several times during the last 40 years with the Calcutta Standard ; its present correction with respect to the latter is accepted as +0″·012. The pressure data obtained with this barometer are being published in the Bombay Observatory Volumes since 1847.

I am grateful to Dr. C. W. B. Normand and Dr. S. N. Sen from whom I received many helpful suggestions during the preparation of this note.

APPENDIX.

SECONDARY STANDARDS.—Of the four barometers employed in turn as a secondary standard at the office of the Meteorological Reporter to the Government of Bengal, Casella No. 636, Casella No. 714 and Adie No. 8/1869 and do not present us with any long or important accounts. In fact after 1875, we do not find any of them being used as a standard. The history of these instruments has therefore been omitted from the note.

Barometers numbered 86, 94, 109 and 112 are all standard barometers of portable type made by J. Newman of London. This type of instrument has a double iron cistern with a solid bottom so that the mercury can be secured easily for travelling ; the scale of the instrument can be moved up and down by means of a tangent screw, thereby making it possible for the index itself to be brought down to a level with the surface of the mercury ; its tube has a large bore to keep down the capillary correction.

No. 712 on the other hand is a standard barometer of Fortin pattern manufactured by L. Casella of London.

All these five barometers have played an important role in the history of barometry in India. In the following pages a brief history of these instruments has therefore been included. In the table accompanying the history of each barometer, the corrections of the latter which were accepted and made use of at different periods are given in chronological order. The amount of change of correction as a result of cleaning, repairs, etc., was determined accurately by comparison with a standard barometer of consistent performance (*vide* columns 2 and 3 of the table) before and after the operation ; in this determination, the correction of the arbitrary standard did not enter. The net change, thus determined, was added to the previous correction of the barometer to form its new correction (*vide* last column of the table).

In this connection it may be said that any investigation into the history of the Calcutta Standard and its contemporary barometers can only be partial, as, many of the earlier records cannot be found, and in the several periods for which there are records it is only by inference that the correction actually used can be determined. Original records of adjustments etc. prior to 1891 are altogether missing; for this period, therefore, the information given here has been solely based on the valuable notes and collected data kept in file by Dr. G. C. Simpson (now Sir George Simpson K.C.B.) while he was associated with this department.

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* Only on 22nd January 1876 it was once carefully inverted to check the mercury click.

[1] C. Chambers, Magn. and Metl. Obsns., Bombay 1865 to 1870, p. ix.

[2] C. Chambers, Magn and Metl. Obsns., Bombay 1871—1878, Introduction p. ix.

1. Barometer, Newman No. 86.

(Bore of the tube=0″·514).

This barometer, Newman No. 86 as it was in the period 1855 to 1877 has been adopted as the ultimate standard for this department. It is difficult to trace now the exact date of purchase and installation of this barometer. It can only be gathered that the instrument was not obtained in India before 1842 and that it was in use before 1855 at the Surveyor General's Office, Calcutta. In March 1877, it was transferred to the Alipore Observatory; but, soon after the transfer, air gained admission into its tube and although it was refilled and repaired several times the performance of the instrument was not found to be satisfactory till 1895. Series of comparisons with Newman 109 showed that it had undergone a change in its correction by —0″·007. Since then, it was employed as a subsidiary standard at the Alipore Observatory. The barometer was cleaned in March 1908 when it showed a change in its correction but a subsequent cleaning in 1927 did not apparently affect its correction. Several parts of the barometer were, however, defective and therefore the instrument was transferred in May 1928 to the Meteorological Office, Poona, where it was repaired and installed.

Barometer, Newman No. 86.

1855 (?) to 1877	Used as the Calcutta Standard ; No index correction was applied to this barometer, its readings being considered as accurate...................... Correction to Kew Standard —0″·009.

Period.	Particulars.	Change of correction.	Correction to Calcutta Standard.
November 1895 to March 1908.	Mean difference from Newman No. 109 (correction = + 0″·005) .. —0″·0118 (5)	..	—0″·007
March 1908 (cleaned).	Mean difference from No. 109. before cleaning —0″·0144 (5) after cleaning —0″·0182 (5)	—0″·0038	—0″·011
March 1908 to September 1927.	Correction maintained	..	—0″·011
September 1927 (cleaned).	Mean difference from No. 112. before cleaning —0″·0163 (3) after cleaning —0″·0160 (3)	+0″·0003	—0″·011
September 1927 to May 1928.	Correction maintained	..	—0″·011
May 1928 to November 1930.	Instrument set up at the Meteorological Office, Poona	..	—0″·019

Figures in parentheses indicate the number of comparisons, each comparison comprising of about 20 observations.

2. Barometer, Newman No. 94.

(Bore of the tube = 0″·526.)

This barometer was originally at the Surveyor General's Office, Calcutta. In 1869 it was removed to the office of the Imperial Meteorological Reporter, Calcutta, for use as a secondary standard. Before removal, 13 readings of comparison with the Calcutta Standard gave a correction of +0″·025. After having been set up in its new site a comparison was again attempted by reading the two barometers, No. 86 at the Surveyor General's Office and No. 94 at the Meteorological Reporter's Office, —simultaneously at some appointed hour. These readings taken on 20 different occasions indicated a correction of +0″·012. This value, however, was apparently considered vitiated and a more thorough investigation in 1871 in which 73 simultaneous readings were used, led Blanford to conclude that the transfer had produced no change in the correction of the instrument and he accepted +0″·025 as the correction[*]. We find that it was employed as the secondary standard till November 1871 and after that date a series of comparisons was undertaken with a view to watch the behaviour of the instrument. It was compared with Casella No. 636 in December 1871 and again in June 1873 ; corrections found on these two occasions, No. 636 *minus* No. 94 were —0″·018 and —0″·017 respectively, showing that the correction of barometer No. 94 had remained practically constant during the period. In January 1874, it was again employed as a secondary standard but was discontinued from May 1874 as it was " damaged " and required repair. After repairs it was compared with Casella No. 636 on two occasions—yielding values of —0″·013 for No. 636 *minus* No. 94. Thus there was a change of —0″·004 in its previous correction since the comparison made in 1873. Hence, after May 1875 we find the correction of No. 94 to the Calcutta Standard as +0″·021 instead of the previously accepted correction of +0″·025. For a long time, however, this barometer was not brought in use.

In April 1904 it was brought into use as a subsidiary standard and as a result of five comparisons with No. 109 its correction to the Calcutta Standard was accepted as +0″·016. When it was cleaned in March 1908, the correction changed to +0″·017. It was again found necessary to clean it in 1918, but while it was being taken down for the purpose, air entered the tube accidentally, and the instrument remained out of action till 1921 when the tube was refilled. Subsequent comparisons indicated that it continued to be somewhat erratic in its behaviour till the end of 1924 after which date it showed a tendency to settle down to a steady correction. It was cleaned in August 1927 but the change in its correction was slight. After December 1929 however, the barometer began to show a steady fall in its correction ; it was therefore removed to Poona for thorough overhaul and repairs.

Barometer, Newman No. 94.

Period.	Particulars.	Change of correction.	Correction to Calcutta Standard.
In 1869 ..	Mean difference from Newman No. 86 +0″·0245	..	+0″·025
Up to April 1874	Correction maintained	..	+0″·025
May 1874 to April 1875 (repaired).	Mean difference from Cas. No. 636. before repair +0″·0175 (2) after repair +0″·0135 (2)	—0″·0040	0″·021

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[*] See Proc. Asiat. Soc. of Beng. 1871 pt. II p. 447. In this article Mr. Blanford gives the number of the Cal. Std. as 84 instead of its correct number 86.

Period.	Particulars.	Change of correction.	Correction to Calcutta Standard.
May 1875 to March 1904 ..	Correction maintained	..	+0″·021
April 1904 to March 1908.	Mean difference from No. 109 (correction = 0″·006). +0″·0104 (5)	..	+0″016
March 1908 (cleaned).	Mean difference from No. 109. { before cleaning. +0″·0096 (5) after cleaning +0″·0104 (5)	+0″·0008	+0″·017
March 1908 to January 1918.	Correction maintained	..	+0″·017
February 1918 to July 1921.	Instrument under repair.		
July 1921 to December 1924 ..	Mean difference from No. 112 (correction = +0″·005). +0″·0122 (4)	..	+0″·017
January 1925 to August 1927.	Mean difference from No. 112 (correction = +0″·005). +0″·0065 (6)	..	+0″·012
August 1927 (cleaned).	Mean difference from No. 112. { before cleaning +0″·0080 (3) after cleaning +0″·0063 (3)	—0″·0017	+0″·011
August 1927 to December 1929.	Correction maintained	..	+0″·011

Figures in parentheses indicate the number of comparisons, each comparison comprising of about 20 observations.

3. Barometer, Newman No. 109.

(Bore of the tube = 0″·500.)

In the latter part of the year 1876, this barometer was transferred from the Surveyor General's Office, Calcutta, to Alipore Observatory and in May 1877, it was very carefully compared with Newman No. 86 and found to require a correction of —0″·0003 which was neglected. Originally this barometer was reading practically the same as Newman No. 86, but unfortunately it was accidentally damaged in 1878. The instrument was refilled in 1890. A considerable change in its correction resulted each time after repairs. After 1890, however, we find that the instrument had settled down, because after cleanings in July 1899, February 1902 and again in August 1927, only slight changes were found in its correction. It is still a very good instrument.

Barometer, Newman No. 109.

Period.	Particulars.	Change of correction.	Correction to Calcutta Standard.
May 1877 ..	Mean difference from Newman No. 86 (correction = 000) .. —0″·0003	..	000
October 1879 (repaired and cleaned).	Mean difference from Newman No. 112. before repairs +0″·0030 (8) after repairs —0″·0050 (8)	—0″·0080	—0″·008
October 1879 to May 1890.	Correction maintained	..	—0″·008
June 1890 (Tube refilled).	Mean difference from Newman No. 112. before refilling —0″·0061 (10) after refilling +0″·0065 (10)	+0″·0126	+0″·005
May 1890 to July 1899.	Correction maintained	..	+0″·005
July 1899 (cleaned)	Mean difference from Newman No. 112. before cleaning. +0″·0068 (6) after cleaning +0″·0092 (5) Mean difference from Newman No. 86. before cleaning. +0″·0114 (7) after cleaning +0″·0133 (6)	+0″·0020	+0″·007
August 1899 to January 1902.	Correction maintained	..	+0″·007
February 1902 (cleaned).	Mean difference from Newman No. 112. before cleaning. +0″·0090 (1) after cleaning +0″·0080 (1) Mean difference from Newman No. 86. before cleaning. +0″·0134 (5) after cleaning +0″·0124 (5)	—0″·0010	+0″·006
February 1902 to July 1927.	Correction maintained	..	+0″·006
August 1927 (cleaned).	Mean difference from Newman No. 112. before cleaning. +0″·0014 (10) after cleaning —0″·0004 (9)	—0″·0018	+0″·004
August 1927 to December 1930.	Correction maintained	..	+0″·004

Figures in parentheses indicate the number of comparisons, each comparison comprising of about 20 observations.

4. Barometer, Newman No. 112.

(Bore of the tube = 0″·525).

This barometer was installed at the Alipore Observatory, Calcutta, in **March** 1877. After comparison with Newman No. 109 in August 1879, its correction to Calcutta Standard was found to be —0″·003. The instrument was cleaned first in October 1901 and then in September 1903, but its correction remained unchanged. In January 1906, however, the position of its fiducial point was altered and its new correction was +0″·008. The instrument was cleaned at the Mathematical Instruments Office, Calcutta, in March 1908 and January 1912 and a change in its correction was found after each cleaning but no change was noticed after its tangent screw for scale setting was repaired in October 1913. Subsequent comparisons, however, indicated that the correction used for the barometer was not quite adequate. In January 1917 therefore this correction was changed to +0″·005. In May 1928, the barometer was again cleaned but no change was noticed in its correction.

This is another good instrument still in excellent condition. Barometer No. 112 and with No. 109 are being used to mantain the standard of the original Newman No. 86.

The history of these two barometers during the period they were used as ‘ primary standard ’ has already been given.

Barometer, Newman No. 112.

Period.	Particulars.	Change of correction.	Correction to Calcutta Standard.
August 1879 ..	Mean difference from Newman No. 109 (correction = 0″·000). —0″·003	..	**—0″·003**
August 1879 to October 1901.	Correction maintained	..	**—0″·003**
October 1901 (cleaned).	**Mean difference from Newman No. 86.** before cleaning. +0″·0046 (5) after cleaning +0″·0040 (5)	—0″·0006	**—0″·003**
October 1901 to December 1905.	**Correction maintained**	..	**—0″·003**
January 1906 (cleaned and fiducial point changed).	**Mean difference from No. 109.** before repair —0″·0084 (7) after repair +0″·0022 (5)	+0″·0106	**+0″·008**
January 1906 to March 1908.	**Correction maintained**	..	**—0″·008**

Period.	Particulars.	Change of correction.	Correction to Calcutta Standard.
March 1908 (cleaned).	Mean difference from No. 109 { before cleaning. +0″·0022 (5) after cleaning —0″·0010 (5)	—0″·0032	+0″·004
March 1908 to January 1912.	Correction maintained	..	+0″·004
January 1912 (cleaned).	Mean difference from No. 109 { before cleaning. —0″·0018 (5) after cleaning —0″·0008 (5)	+0″·0010	+0″·005
January 1912 to May 1928.	Correction maintained	..	+0″·005
May 1912 (cleaned)	Mean difference from No. 109 { before cleaning. 0″·0000 (3) after cleaning +0″·0003 (3)	+0″·0003	+0″·005
May 1928 to date	Correction maintained	..	+0″·005

Figures in parentheses indicate the number of comparisons, each comparison comprising of about 20 observations.

5. Barometer, Casella No. 712.

(Bore of the tube = 12·5 m.m.)

This is a standard barometer made by L. Casella of London. It is of the usual Fortin pattern but provided with a larger tube and cistern.

In October 1907, the instrument was obtained through the P. W. D., Bengal, from the R. I. E. College, Cooper Hill, London. After slight repairs to its vernier-screw and cistern lid it was installed at the Alipore Observatory in February 1908. Compared with Newman No. 112 in March 1908, the barometer showed a correction of +0″·012 with respect to the Calcutta Standard ; but several comparisons during that year indicated that its correction was not being maintained. Tests were then made on the thermometer which was originally attached to the case of the barometer. The thermometer was found defective and was therefore replaced by a good one. A glass tube filled with mercury was placed by the side of the barometer at a height of about 14 inches from the cistern and the new thermometer was inserted into the tube.

The barometer was found to have settled down only in 1911 and, we find, its use as a sub-standard was made actually after that date. From a series of comparisons ending in 1914, it was found that the barometer had a correction of +0″·015 with respect to the Calcutta Standard. That correction was accepted with effect from the date of installation of the instrument. The barometer was cleaned in July 1920 and again in August 1927, and a change in its correction was found after each cleaning.

The record of its performance since August 1910 was considered to be very satisfactory. In May 1928 it was transferred to Poona and installed there as a working standard.

Barometer Casella No. 712.

Period.	Particulars.	Change of correction.	Correction to Calcutta Standard.
March 1908 ..	Mean difference from Newman No. 109 (correction = +0″·006) +0″·009 (2)	..	+0″·015
March 1908 to July 1920.	Correction maintained	..	+0″·015
August 1920 to July 1927 (cleaned).	Mean difference from Newman No. 112 (correction +0″·005). +0″·008 (12)	..	+0″·013
August 1927 (cleaned).	Mean difference from Newman No. 112. before cleaning. +0″·008 (3) after cleaning +0″·007 (3)	—0″·001	+0″·012

Figures in parentheses indicate the number of comparisons, each comparison comprising of about 20 observations.

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Synoptic and aerological study of a thunderstorm-day at Agra, December 3rd, 1936.

BY

S. Basu and Ram Sahay.

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SYNOPTIC AND AEROLOGICAL STUDY OF A THUNDERSTORM-DAY AT AGRA, DECEMBER 3rd, 1936.

BY

S. BASU AND RAM SAHAY.

(*Received on 28th March 1939.*)

Abstract. A line-squall passed over Agra at about 10·30 a.m. on the 3rd December 1936. On that day two sounding balloons with meteorographs were let off, one at about noon, after the passage of the squall, and the other in the afternoon at about 5 p.m. Both these instruments were later retrieved, and their records were found to reveal some very interesting features. An examination of all the available data was therefore undertaken to study the weather situation of the day. The examination suggests the thunderstorm to have been caused by the passage of a cold front in association with the secondary low of a western depression over east Rajputana. The front was a weak one inasmuch as the southward and eastward flow of the cold dry air was not maintained in the wake of the front; on the other hand, the region traversed by the cold front was overrun by a comparatively warmer and moister air within 12 hours of the passage of the front. A rough calculation of the slope of the cold front at noon and evening of the 3rd December 1936 is given. The analysis suggests a probable surface of subsidence to have existed in association with the front.

1. Introduction.

On the 3rd December 1936 a line squall passed over the Upper Air Observatory, Agra, after 10 o'clock in the morning. One sounding balloon was let off at about noon and another at 17 hours in the afternoon. Both the meteorographs were later retrieved. On working out their records they revealed some interesting features regarding the air masses over Agra on the 3rd. It is proposed here to examine the synoptic situation leading up to the thunderstorm and to examine the temperature and humidity in the upper air near Agra with reference to the air masses taking part in the weather of the day.

2. The Synoptic situation.

In association with the passage of a western depression eastward across northern India during the 1st and 2nd December a secondary depression had formed over Sind ; there was fairly widespread rain in the Punjab and Kashmir and a few falls also occurred in Baluchistan, west Rajputana and the west U. P. By the 2nd morning pressure had risen generally over northwest India, only a shallow trough of low pressure remaining across Kathiawar and Central India. During the next 24 hours there was again a considerable fall of pressure within this trough ; and by the 3rd morning a depression of small extent but with a well marked wind circulation around it, again appeared over east Rajputana : at 8 hours its centre was near Kotah. The deficiency of pressure from the normal, near the centre of the depression, was of the order of ·01 of an inch. The 8 hours weather map for the 3rd is reproduced in *Fig. 1.*

It will be seen that a line of discontinuity (shown by the double line in *Fig. 1.*) was lying across west U. P. and east Rajputana, passing a little to the west of Agra. To the east or southeast of the line the ground winds were either calm or from an easterly to southeasterly or southwesterly direction generally ; while to the north and west of the discontinuity the ground winds were generally from some northwesterly direction. Also, there was discontinuity in the kind and amount of cloud ; skies were practically overcast with a predominance of cumuliform clouds on the western side of the discontinuity, and generally clear, or lightly clouded with stratus type clouds, on the eastern side of it. The discontinuity therefore appears to mark out a zone of separation between two air currents, the zone being narrow enough to exhibit the characteristics of a front. An examination of the distribution of rainfall and the past weather at stations on either side of the discontinuity lends support to the existence and activity of a front over the region. An appreciable contrast of temperatures is noticeable at the front. But it is difficult to ascertain to what extent this contrast represents actual differences in the temperatures of the two air masses ; because, the stations showing a lower temperature were mostly those which had had appreciable rain during the preceding 24 hours and which had a low cloud ceiling, while those showing the higher temperatures reported little cloud and had not recorded rain uptil then. So that most of the temperature contrast, as noticeable on the surface weather chart, might have been due to rain cooling and effects of insolation differently affecting the stations on the two sides of the discontinuity.

In *Fig. 2* is reproduced the afternoon weather chart for 17 hours of the 3rd. This shows that the northerly air, though extending somewhat to the eastward during the day, remained more or less confined to the U. P. and the southeast of the Punjab. Over the rest of northwest India the surface winds had become mostly light variable. A comparison of the upper winds over Agra in the morning and afternoon (see *Figs. 3 and 4*) is interesting. It appears that the cold front in the morning was constituted by the pushing of a shallow southeasterly air current of about 1 km. thickness by a westerly to northwesterly, apparently colder, air current. Later in the evening the further flow of the northwesterly current had markedly weakened and there was a general overrunning of Agra and the neighbouring regions by a westerly to southwesterly air mass from the surface up to about the 3 km. level ; this is borne out by the pilot balloon observations of the next morning.

3. The passage of the cold front over Agra.

During its travel eastward and southward the cold front affected Agra, among other stations ; a line-squall passed over the Upper Air Observatory between 10·15 and 10·30 hours. The autographic records of the meteorological elements are given in *Fig. 5.*

Prior to the arrival of the line-squall there was only 2-5 m.p.h. easterly wind from about 3 a.m. up to about 8 a.m.; thereafter the wind speed gradually increased, veering at the same time. By 10 a.m. a south-southeasterly wind of about 10 m.p.h., slightly gusty, was blowing over the station, the velocity falling to about 5 m.p.h. by 10·25. At this time there was a sudden change, the wind changing to northwesterly; its speed increased to about 18 m.p.h., gustiness also increasing at the same time. This was the time when the line-squall passed over the Observatory. A thunderstorm followed between 10·45 and 11·15. The arrival of the northwesterly air by about 10·30 is marked on the thermograph chart by a fall of the dry bulb temperature of 11°F., from 76°F. to 65°F., within twenty minutes, there being a corresponding fall of only 2°F. in the wet bulb temperature. At the same time, the barograph shows a sudden rise of pressure by about ·01 of an inch. The thunderstorm was attended in the beginning with a sharp shower which commenced at 10·45 hours; a few minutes before the arrival of the sharp shower there was slight rain from dark cumulonimbus clouds. Attending the rain and the fall of temperature the hygrograph shows an increase of relative humidity from 45% to 95%.

After the first shower the weather remained cloudy, intermittent rain continuing up to about 14 hours. The wind speed had however decreased after 11 hours, the direction continuing to change through northeast and east practically up to 19 hours. Between 18 and 21 hours thunder occurred again with two sharp showers at about 19·15 and 21·15 hours respectively; during this period the wind direction was changing, and eventually it became southeasterly. The barograph recorded fairly rapid fluctuations during the period of rapid wind variation. By about midnight the wind practically died down.

It would appear from the study of the autographic records at Agra that the first thunderstorm was associated with something in the nature of a cold front passing over the station. But the subsequent weather over the station is very different from what might be expected in the wake of simply a cold front. This, on the other hand, suggests, that the front, which was a weak one, brought in its rear a northwesterly air the flow of which, however, did not continue. It rather withdrew, after causing the initial thunderstorm, yielding place to the southwesterly air mass which was, under the influence of the weather situation then prevailing, trying to overrun the region. The southwesterly air apparently gained over the northwesterly or westerly air by about 8 p.m. over Agra when the second spell of rain, drizzle and thunderstorm occurred over the station.

4. Progress of the Front.

In *Table I* below are given the extracts from the weather diaries kept at stations which were situated on the two sides of the line of discontinuity and which were affected by the front.

TABLE I.

1. Hissar ..	.. Thunderstorm 0345 up to 0500; slight shower 0420—0515; thunderstorm again 0620—0640. Sky was quite dark towards SE till about 0700. It was almost an overcast sky after 1000 with AK and SK; lightning was seen towards NE from about 1800 and the moon was bright.
2. Jaipur ..	.. C and CS developed into KN in the early hours of the morning. Moderate thunderstorm, slight drizzle and shower 0600—0610. After this the sky cleared somewhat but became overcast in early afternoon with thunder from 1400—1600. Sky remained ugly till evening. Night cloudless.
3. New Delhi	.. Thunderstorm commenced at 0600, preceded by loud thundering and lightning. Rain stopped at 1120. Sky remained thickly clouded throughout the day followed by thundering again towards 1800.

4. **Ajmer** ..	.. Drizzle 0445—0447. Rain with thunder and lightning 0645—0655.
5. **Aligarh** ..	.. The sky clouded ; wind suddenly increased at 0830 and remained quite fast till there was continuous rain from 1015—1100. Then a slight drizzle at 1330 upto 1430. The night remained threatening, lightning and thunder *at* 2230.
6. **Agra** ..	.. Cirrus appeared early morning from the west, SK cloud appeared at 0800 hrs. and rapidly increased and changed into KN at 0900 hrs. with thunder at 0940 to 1020 hrs. Line-squall from 1020 to 1030 hrs. appeared from the west, wind changed from southwesterly to northwesterly maximum force 19·2 m.p.h. Thunderstorm with slight rain continued from 1045—1115, thunderstorm and drizzle 1115—1130, rain 1210—1300, rain 1330—1405, thunderstorm 1230—1415 and 1800—2100, rain 1910—1920. drizzle 1925—2100, rain 2115—2130, drizzle 2130—0115, lightning 2100—2310. Night overcast till 0200 hrs. afterwards sky cleared gradually.
7. **Mussoorie**	.. Overcast in the morning. Rain about mid-day followed by thunder. Dense fog in the afternoon. Rain again at night.
8. **Dehra Dun**	.. From the early morning we had K and AK covering the whole sky. After 1000 cloud had gathered so much that we had drizzle between 1300 and 1800. After that till 1900 we had low clouds. After 1900 it began clearing, and by 2000 all cleared and became cold. Dew began to fall.
9. **Mainpuri**	.. Early morning CK clouds were visible, wind direction was E. After 1100, AS clouds began to appear very rapidly. After 1300 the sky was overcast with KN, SK and N clouds ; thunder heard at 1415 ; lightning from 1410 to 1430 ; afterwards showered ; after 1600 there was opening in the sky—again thunderstorm at 1955 and rain from 2002 to 2020 ; afterwards drizzle. Night cooler than usual.
10. **Bareilly**	.. Morning foggy and slightly cloudy. Thunder followed by rain at 1400. Slight rain at 2030.
11. **Jhansi** ..	.. Weather fine till noon when K clouds began to appear which soon thickened into low SK clouds ; followed by thunder and occasional drizzle from 1500 ; intermittent rain 2100—2300 followed by occcasional thick drizzle.
12. **Roorkee**	.. Sky was thickly clouded up to 1000 ; afterwards cleared ; there was NE wind up to noon and NW in the afternoon. Drizzled between 1515 and 1530 and from 2100—2130. Cooler than the previous day.
13. **Muktesar**	.. C appeared in the morning ; clouds increased and changed into N. Rain 1530—1620. Evening also cloudy and rain during night.
14. **Brijnagar**	.. Fair weather all day ; intermittent drizzle for a few minutes at 1640. Lightning was seen in the evening.

N. B.—The times mentioned in this table are Indian Standard Times (5½ hours ahead of Greenwich Mean Time.)

It is significant to note that at most of these stations there was one feature common with Agra, *viz.*, that the cold front thunderstorm was not followed by clearing weather but by a second spell of more or less rainy weather (sometimes accompanied by thunder) a cloudy interval occurring between the two rainy spells. From the time-sequence of the occurrence of the first thunderstorm at the various stations, coupled with the probable lie of the front on the morning chart, it is possible to work out approximately the speed with which the front (thunderstorm) moved over the region which it affected. In *Fig. 6* are plotted the isochrones for the cold front as interpolated from the times of occurrence of the first thunderstorm. From the points on the 10 and 14 hours isochrones nearest to Agra, the speed obtained for the travel of the cold front is approximately 26 km. p. h. or 16 m.p.h. This gives a general confirmation of the travel of the discontinuity between 8 and 17 hours as shown on the

morning and evening maps if it is assumed that the front continued to move at about the same *average* speed between these hours.

The time-sequence of the incidence of the second rainy spell at the different **stations was also plotted** on a map : this shows the advance of the southwesterly air over the cold air.

The isochrones for this front are shown in *Fig. 7.*

5. Upper Air Data.

To study this thunderstorm two sounding balloons were let off carrying Dines' type meteorographs as improved by G. Chatterji at the Upper Air Observatory, Agra. The instruments are calibrated for pressure, temperature and humidity, and a final test mark corresponding to a particular temperature and pressure is given to the instrument, just before being let off to determine any shift of pressure and temperature that might have occurred in the calibration grid of the instrument during its detention before being let off. The balloons were made of 4 segments of saul rubber sheeting and had circumferences of about 400 cm. when inflated. The free lifts given to the two balloons were 600 and 500 gm. respectively ; allowing for the weight of the balloon, the instrument and its cage, etc., these lifts correspond to a rate of ascent of 10 to 11 km./hr. under ordinary conditions. The calibration marks and records of the instruments are obtained on graphited plates which are scratched by the scribing pens of the meteorographs.

The first instrument was let off at 1211 hours I.S.T. with a radiation cover to minimise, as far as possible, the effect of solar radiation on the instrument. This instrument was recovered at a distance of 284 km. from Agra and at an angle of 72° from the north. The other instrument which was let off without a radiation cover at 1710 hours in the afternoon was retrieved at a distance of 177 km. at an angle of 70° from the north. The height-temperature-humidity diagrams as worked out from the records are reproduced in *Fig. 8.*

The first instrument registered an extraordinary record. It is seen in this record that beginning from about 4 gkm. level there is a layer through which a very rapid drop of temperature occurs, the temperature at about 4·9 gkm. being nearly 20°C. lower than at 4 gkm.: after 4·9 gkm. the record shows a break. Thereafter the record shows no trace till the 8 gkm. level: after this the trace again becomes available for the higher levels. On the face of it, it would be difficult to explain this observation and one will be led to doubt the accuracy of the record itself. But we shall return later (p. 75) to this feature of the curve and attempt an explanation thereof in view of the possibility of genuineness of this singular feature.

Above 4·9 g km. the first record shows no trace up to the 8 gkm. level ; after this break the trace is visible again for the higher levels. The descending curve ends just below the 2 gkm. level, at a temperature of 282°A (pressure about 800 mb.). It seems very probable that the balloon on reaching the 4·9 gkm. level was caught in a descending current and on coming down to below 2 gkm. the water release worked. This contrivance devised by G. Chatterji, is used with the instrument for removing the recording pen off the plate at descent for avoiding blurring of the lower part of the record, when the instrument strikes ground (1). Thus at this level the pen was lifted off the graphited plate. Then the balloon began ascending again and on reaching the 8 gkm. level the pen again came in contact with the plate, for it is at about this height that the contact is ordinarily expected to be re-established. So, the trace is resumed above 8 gkm.

One of the traces of the record of the first instrument shows a break between 12·5 gkm. and 15·5 gkm. and a large difference of temperature of the order of 38°C

between the ends of this break; this is probably the descending trace. It will be noticed that the separation between the two traces of the record from 12·5 gkm. to 8 gkm. decreases as the lower levels are reached. A probable explanation which has been suggested for this feature is that for some reason or other the balloon burst at 15·5 gkm. and the fabric dropped down over the instrument. The large difference (decreasing as we go lower) of temperature between the two traces of the record from 12·5 gkm. to 8 gkm. and the blur at 15·5 gkm. probably lend support to this view. As to how and why the balloon survived the highest altitude attained by it and why it should have burst during the descent however remains unexplained.

In *Table 2* below are given the temperature and humidity values at various heights over Agra obtained from the two sounding balloon records.

TABLE 2.

DATA AVAILABLE FROM SOUNDING BALLOON ASCENTS ON 3RD DECEMEBER 1936.

Height gkms. a. s. l.	1211 hrs. I. S. T.		1710 hrs. I. S. T.	
	Temperature. °A.	Humidity. %	Temperature. °A.	Humidity. %
Surface	291·5	95	292·5	85
0·5	293·0	83	290·0	82
1·0	288·0	81	290·5	71
1·5	283·0	..	287·5	85
2·0	280·5	96	284·5	95
2·5	277·5	97	279·5	103
3·0	275·0	98	276·0	104
4·0	271·5	97	270·5	90,104
5·0	..	..	264·0	83
6·0	..	..	257·5	57
7·0	..	..	249·0	..
8·0	..	..	242·0	..
9·0	240·0	..	233·5	..
10·0	231·5	..	226·0	..
11·0	226·5	..	219·5	..
12·0	225·0	..	218·0	..
13·0	221·0	..	212·5	..
14·0	219·0	..	209·0	..
15·0	216·0	..	207·5	..
16·0	211·0	..	204·5	..
17·0	213·0	..	204·0	..
18·0	215·0	..	..	..

Referring to the noon ascent, after traversing an inversion layer from the ground to about ½ gkm. above sea level, an average lapse rate of the order of 10°C/ gkm. is met with up to about 1·5 gkm.; the average value of relative humidity in this layer was 80 per cent. to 85 per cent. Above 1·5 gkm. the lapse rate decreased to about 5°C/ gkm. and the relative humidity increased to more than 95 per cent. It is thus quite apparent that at about noon (a couple of hours after the incidence of the initial thunderstorm and, therefore, of the passage of the cold front over the observatory) the thickness of the dry cold north-westerly air was about 1·5 gkm. This is probably another illustration of one of the frequently occurring cases in which the real temperature inversion is absent above the cold air mass. The frontal surface appears merely as a layer of subnormal lapse-rate and increase of humidity upwards. The following quotation from J. Bjerknes (2) is relevant in this connection.

"When I seize the opportunity of emphasising their (Stuve and Diesing's) result once more, I do it in order to advise against the useless schematic search for real temperature *inversions* at the polar front surface. I feel it so much more my duty to do this as I am unfortunately responsible for the false idea that the warm front and cold front surfaces should necessarily show true inversions of temperature associated with high relative humidity above and low underneath. In fact, this ideal case is not very common."

It will be seen that in the height-temperature diagram also, a change in lapse rate occurs at about 1·7 gkm. After 5 and 7 minutes respectively of the release of this meteorograph, lightning flashes were actually observed twice near the balloon. Taking the rate of ascent of the balloon to be 11 km. per hour the height it would ascend in 5 to 7 mts. will be of the order of 1·3 km. above Agra or 1·5 km. above sea level. At about 1·5 gkm. blurs occur at two places just near each other; at these places the instrument was subjected to changes of temperature of the order of 4°C. to 6°C. indicating the possibility that the blurs might be due to the lightning flashes. It may be mentioned that this level agrees well with the height of the base of the low clouds (KN & SK) at 14 hours, the time of the afternoon pilot balloon ascent : it also agrees with the level where occurred a backing of the wind—(see the pilot balloon trajectory reproduced in *Fig. 9*). These lend additional support for the inference regarding the height of the cold air mass. Above 1·7 gkm. was the warmer air mass with a lapse rate of 6°C./gkm. and relative humidity 97%.

Unfortunately there is a break in the record after 5 gkm., and we cannot fix the upper limit of the moist layer. However, the increase of lapse rate above 4 gkm. to a large superadiabatic gradient up to 5 gkm. makes it possible that above this level (4-5 gkm.) it again met with a dry cold current. The fact that the relative humidity shows little change between 4-5 gkm. cannot be interpreted as either in favour or against this surmise. For it is well known that the hair hygrograph has a particularly large lag coefficient at low temperatures and low relative humidities ; hence the recorded value of relative humidity is likely to be higher than the actual(³). Mixing due to convective processes should also be allowed for when drawing inferences from the humidity record.

The inversion layer in the lowest half kilometer occurs frequently within the cold land air mass in northwest India in winter. These inversions are known to persist through the first half of the day, and sometimes, under favourable conditions, even up to the evening.

In the record from the afternoon ascent, we come across a lapse rate of about 7·5°C./gkm., and relative humidity 80–85%, from the ground level to ½ gkm. above sea level. Between ½ and 1 gkm. is met with an isothermal layer with a decrease of humidity to about 70%. This probably corresponds with the inversion met with in the noon ascent between the ground and ½ gkm. This raising of the stable layer near the ground is to be expected as a result of mixing due to turbulence, both mechanical and thermal. The ascent continues up to 2 gkm. through a lapse-rate of 6°C./gkm., humidity further increases to nearly 100%, the lapse rate being maintained at about 7°C./gkm. Suddenly, after 4 gkm. the humidity falls down to 83% at 5 gkm. and to 57% at 6 gkm. In this ascent which took place well after the passage of the front over Agra, the sharp discontinuity of lapse rate of temperature found in the noon ascent above 1·5 gkm. is not noticeable. On the other hand the average value of the lapse rate in the afternoon ascent ranges between 6·5° and 8°C./gkm., values intermediate between the lapse rates characterising the two air masses in the noon ascent, *viz.*, 10° and 6°C./gkm. This is probably what one should expect as a result of turbulent mixing taking place throughout the convective region over an active front. However, a rise of humidity to about 95%, and later to 100%, is still noticeable at the 2 gkm. level which is $\frac{1}{2}$ gkm. higher than the corresponding level in the noon ascent. The 2 gkm. height thus appears to be the limit up to which the cold air mass was present at 17 hrs. when the second meteorograph ascent was made.

In the evening ascent, the fall of humidity occurring between 4 and 6 gkm. shows that the warm moist air mass may have been limited in thickness to about 5 gkm. ; above that height the ascent was through dry cold air mass of land origin, probably being the air mass normally met with at these heights over north-west India in winter. Unfortunately, the humidity values for the corresponding levels are not available in the noon ascent ; therefore it is not possible to compare the vertical extent of the moist air current at mid-day.

6. Further Inferences.

From the foregoing considerations, it is possible to obtain a rough idea of the slope of the wedge formed by the cold, dry air at the time of the noon and the evening ascents.

In section 4 before, the approximate speed of travel of the cold front was found to be about 26 km./hr. Assuming this speed to have been maintained unaltered between 10·30 I.S.T. (when the front passed over the observatory) and 12·10 I.S.T. (*i.e.*, in $1\frac{2}{3}$ hrs.) the front should have advanced 5/3 × 26 or nearly 45 km. in the direction of its motion. Also, at 12·10 I.S.T. the cold air extended up to 1·5 km. in height over Agra as shown in the preceding section. These indicate an inclination of the cold air as 1·5 in 45 or 1 : 30. This is of the same order of quantities as those slopes met with at the polar front of extra tropical cyclones(4).

Now, take the evening ascent : This ascent was made at 17·10 I.S.T. *i.e.*, $6\frac{2}{3}$ hrs. after the passage of the front over Agra. We may assume the average speed of travel of the front to have been 26 km./hr. during this interval also ; this assumption is justifiable from the respective positions of the front on the morning 8 hrs. and evening 17 hrs. weather charts for the day, and from the map showing the isochrones for the cold front (*Figs. 1, 2 and 6*). So that at 17·10 I.S.T. the front had advanced 20/3 × 26 or nearly 180 km. beyond Agra in the direction of its motion. Also, at 1710 I.S.T. the depth of the cold air was found to be 2 km. Therefore, at this time the slope comes out to be 2 in 180 or 1 : 90.

It is interesting to note therefore that the wedge had been flattening during its passage eastward and southward, so that, in 5 hours, the slope had decreased from 1 : 30 to 1 : 90. This would suggest a spreading out of the cold air with consequent subsidence within itself. Now, if this inference is valid for the lowest part of the cold air, then it is not unlikely that the main body of the cold air mass aloft also was sliding downwards at a probable surface of subsidence in association with the front. For a further evidence of this, we refer back to the height-temperature curve for the noon ascent over Agra (*Fig 8*). It was noticed before (see p. 71) that the balloon met with a layer of superadiabatic lapse-rate between 4 and 5 gkm. above which there was a break in the trace which has been explained as having been due to the fact that at that height a downward current was encountered. It has also been shown that even in the lower layers the cold air had a lapse-rate of about 10°C./gkm. (at the time of the noon ascent) which, with a relative humidity of nearly 80%, is a superadiabatic lapse-rate : thus it is safe to infer that the cold air mass at levels above the moist air-tongue also had a superadiabatic lapse-rate during the forenoon. Now, if this cold air mass had initially a superadiabatic lapse-rate, and downward movement started within the body of this air mass at a surface of subsidence, what would be the effect ? Evidently, the effect of such subsidence would be to produce a vertical temperature gradient more superadiabatic than the original(5). This will explain the large value of the temperature lapse-rate met with between the 4 and

5 gkm. levels in the noon ascent, which has been already shown (see p. 73) to be the level immediately above the frontal surface separating the warm, moist air below and the cold, dry air above.* The above view may be substantially correct ; thus we may have been dealing with a case of subsidence at an inclined surface associated with the front and this may be one of the reasons why the development of precipitation in larger quantity was not favoured round about Agra on the 3rd morning. Later on, during the evening ascent, the highly superadiabatic gradient is no more in evidence, as is to be expected after the effects of turbulence, owing to the thunderstorm and to the advancing day, had held the field for sometime.

From the above discussion one should imagine the structure of the atmosphere over Agra at about noon of the 3rd December 1936 to be somewhat as represented schematically in *Fig. 10.*

7. Acknowledgment.

We wish to record our thanks to Rai Bahadur G. Chatterji, Superintending Meteorologist, Upper Air Observatory, Agra, for the use of the ærological data collected under his direction. We are indebted to the Meteorological Offices, Poona and Karachi (Weather Sections) for the loan of their daily working weather charts and to those members of staff of the Upper Air Observatory, Agra, who helped in working out the meteorograph records, computing the tables and preparing the diagrams for this paper. Our thanks are also due to Mr. S. L. Malurkar for some helpful discussions at the initial stages of the examination of the sounding balloon records.

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4. J. Bjerknes—Diagnostic and Prognostic application of Mountain Observations—Geof. Publ., Vol. III, No. 6 (Section V, p. 21, last para.).
5. J. Namias—Subsidence within the atmosphere—Harvard Meteorological Studies, No. 2, 1934, pp. 7-8.

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*It may be mentioned here that the record of 3rd December 1936 is not an unique record showing a lapse-rate of 20°C. per Km. There was an ascent on the 20th December 1929 at 0911 hrs. which shows a superadiabatic lapse-orate of about 20°C. per Km. for a thickness of about half kilometer at the height of about 2·5 Km. The Weather Diary of Agra for the 20th December is given below.

Weather at Agra on the 20th December 1929.—Early morning to 0718 hrs. N 10 with slight drizzling. 8 hrs.-fog, continued till 9 hrs. (Fog appeared on horizon at 5 hrs.) 10 hrs.-Stratus clouds covered the whole sky. 12 hrs.-Stratus 10, passing from southeast, 14 hrs.-KN 10. 17 hrs.-KN 9 tending to disappear. 18 hrs.-Stratus 6 disappearing fast. Night-passing clouds. A weak depression with definite wind circulation over Kathiawar on the 19th morning lay over C. P. on the 20th morning and became unimportant by the 21st morning. A line of discontinuity lay near Agra extending towards Jhansi on the 20th morning. Thus the synoptic situation was similar to that of 3rd December 1936. Pilot balloon ascents on the 20th December 1929 were failures but one observer had seen the pilot balloon entering and again appearing in view, from the clouds above, at 0750 hrs. (an hour and a quarter prior to the sounding balloon ascent) showing the existence of downward current. It is likely therefore that this was another case of subsidence giving rise to lapse-rate of the order of 20°C. per Km. It is difficult to analyse this earlier case as the data above 4·5 Km., for the records are not available.

The case of subsidence increasing the instability in an air mass is naturally regarded as not to be observed in the atmosphere; but the instance under examination would lead one to imagine that though very rare, it may not be impossible that this is realisable.

M20DGofOb—425—8-11-40—GIPS

Plate I

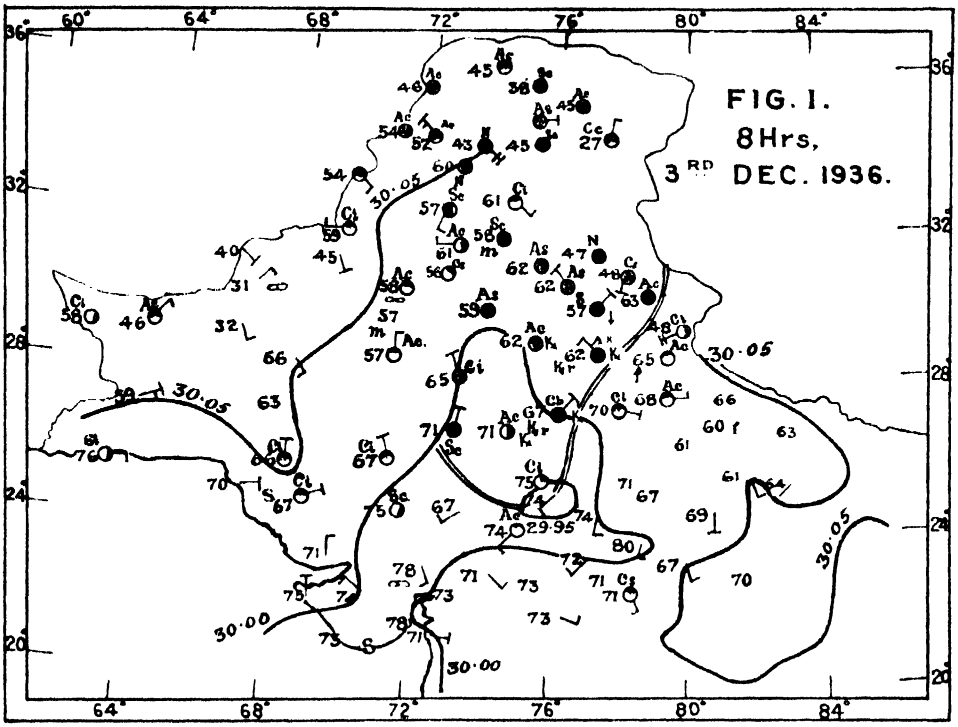


FIG. 1.
8 Hrs,
3RD DEC. 1936.

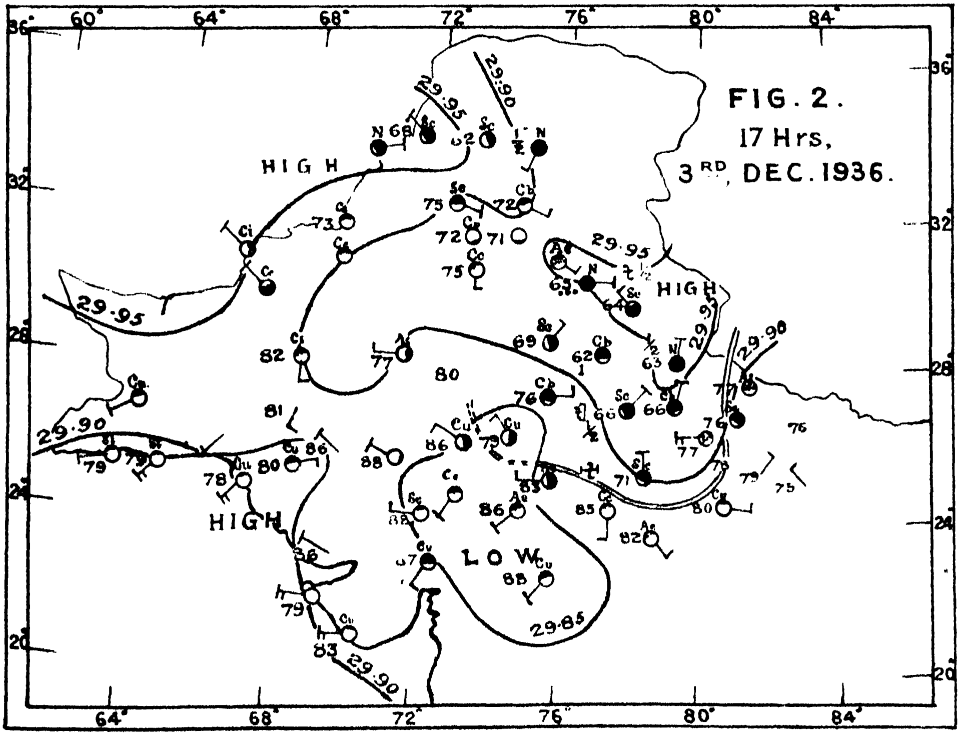
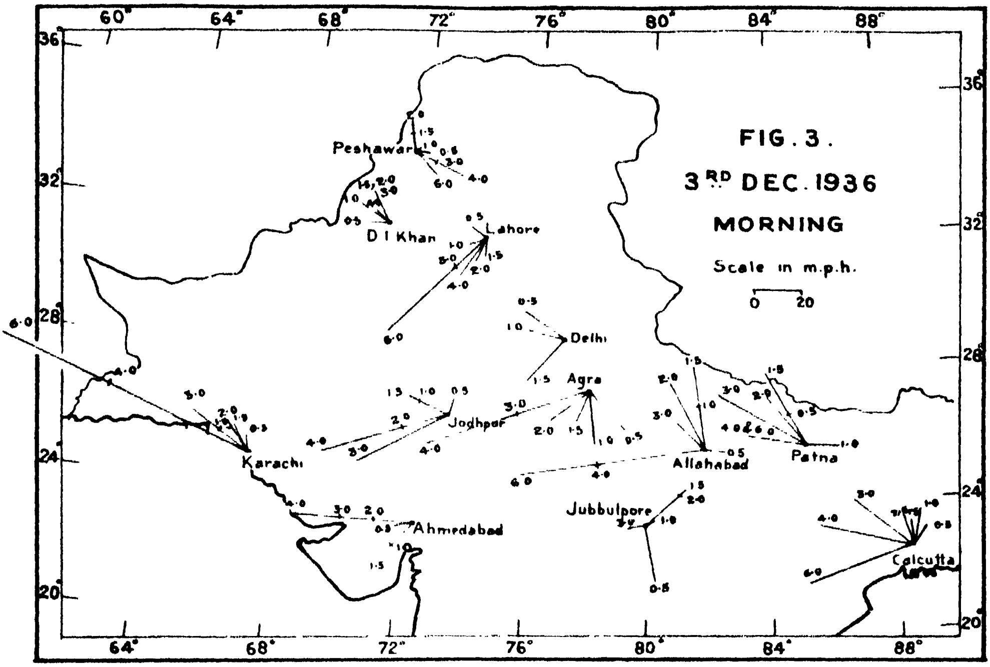
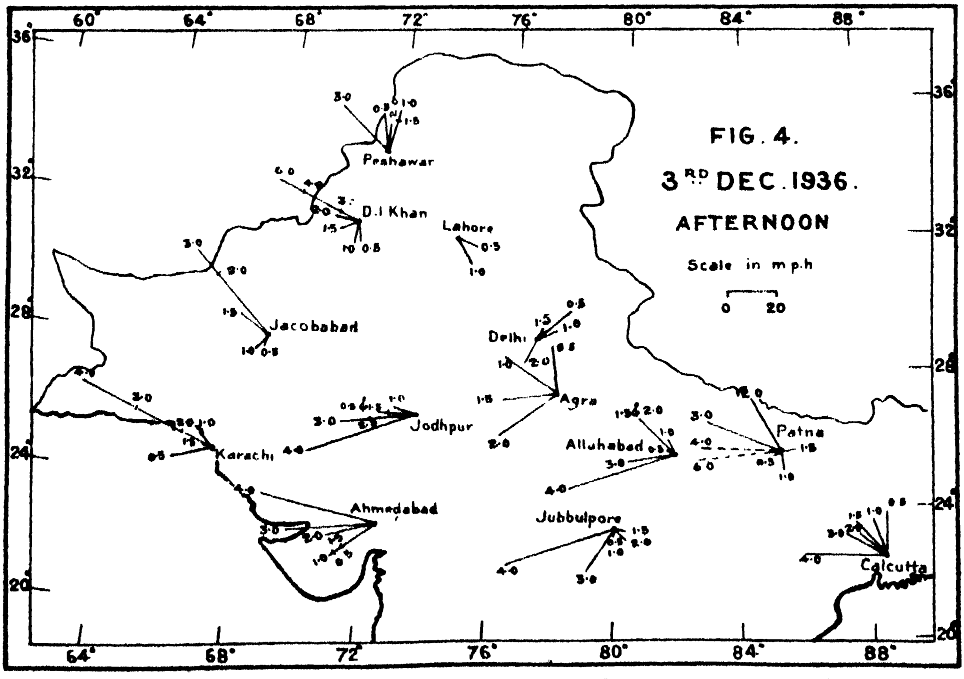


FIG. 2.
17 Hrs,
3RD DEC. 1936.

Plate II



Figures at the end of the wind vectors give the level in kilometers.



Figures at the end of the wind vectors give the level in kilometers.

Plate III

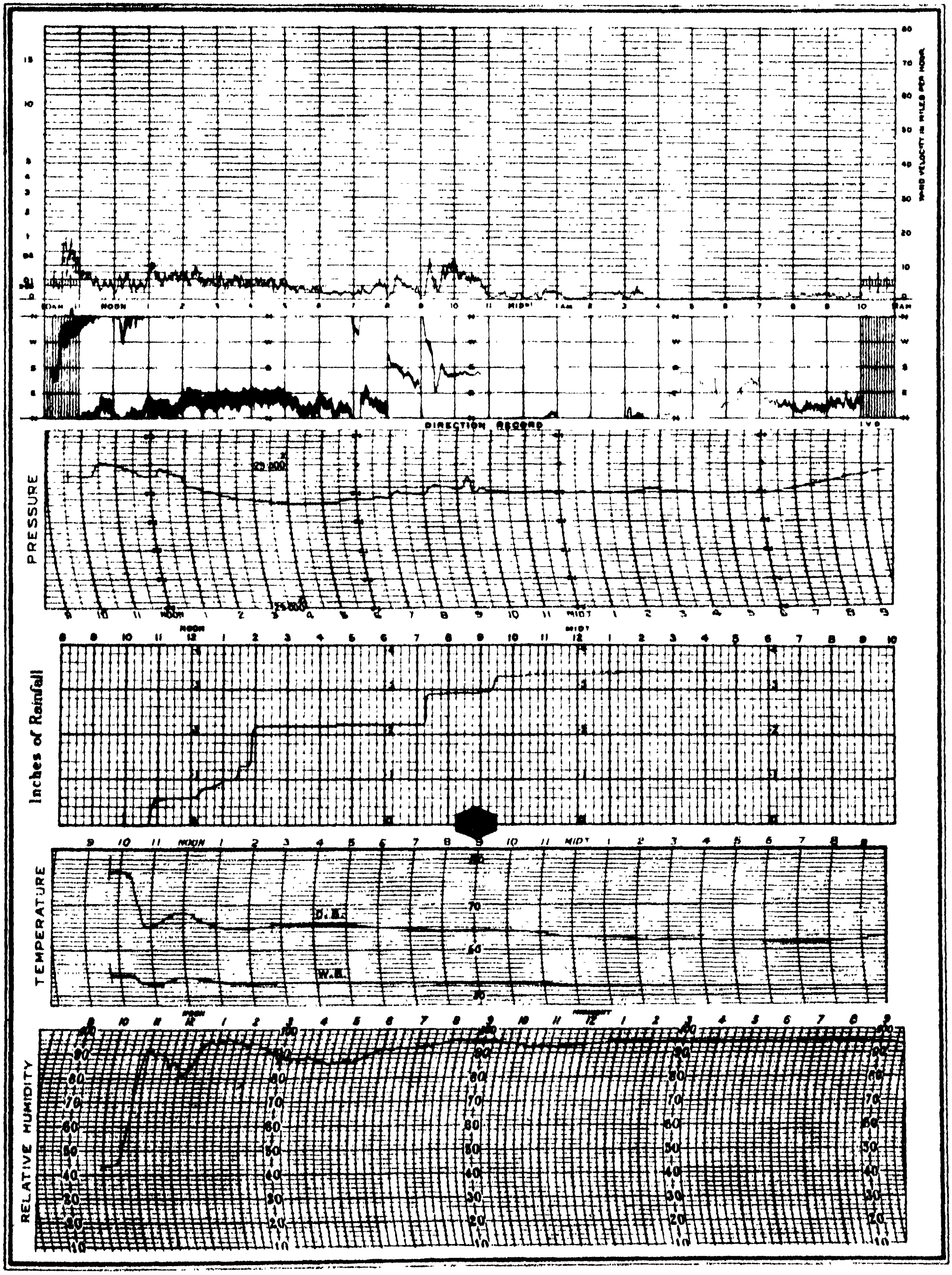


Fig. 5. Wind, Pressure, Rainfall, Temperature and Relative Humidity at Agra.
3RD - 4TH December 1936.

G P 7 O Poona, 1940

Plate IV

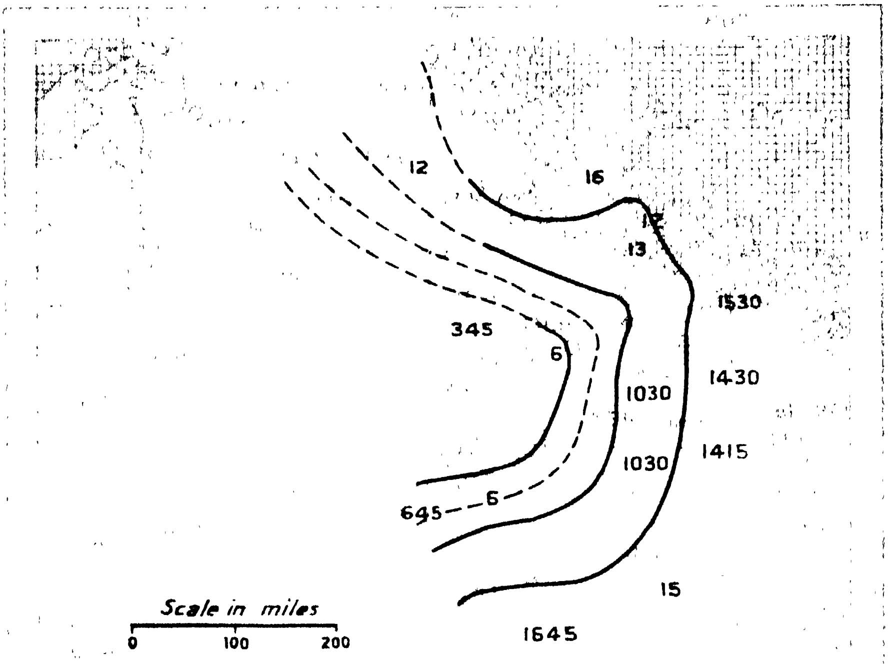


FIG. 6. ISOCHRONES OF THE FIRST (COLD) FRONT.
MORNING TO AFTER-NOON, 3RD DEC. 1936.

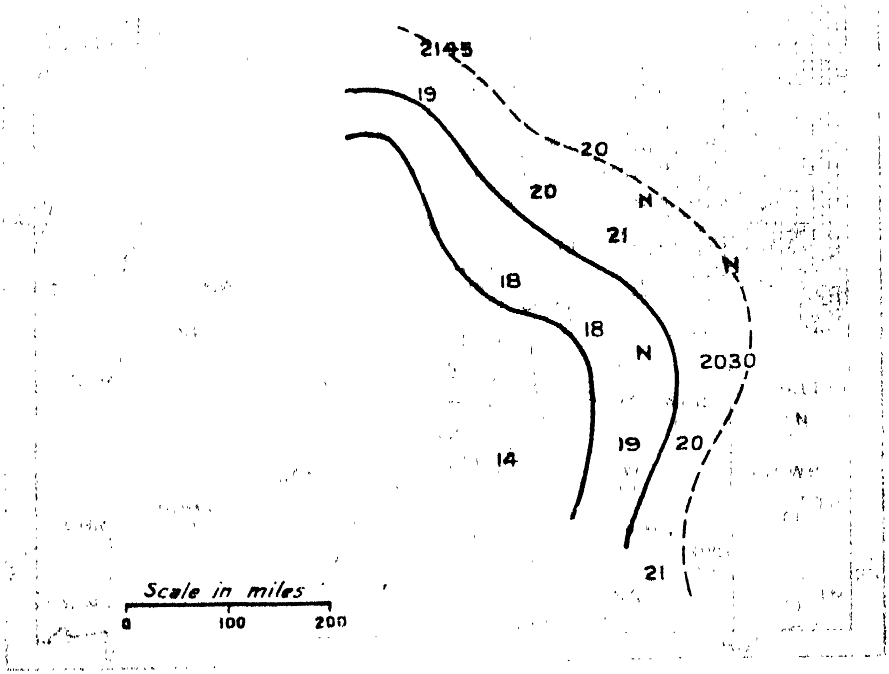


FIG. 7. ISOCHRONES OF THE SECOND FRONT.
EVENING, 3RD DEC. 1936.

Agra soundings, 3rd Dec. 1936.

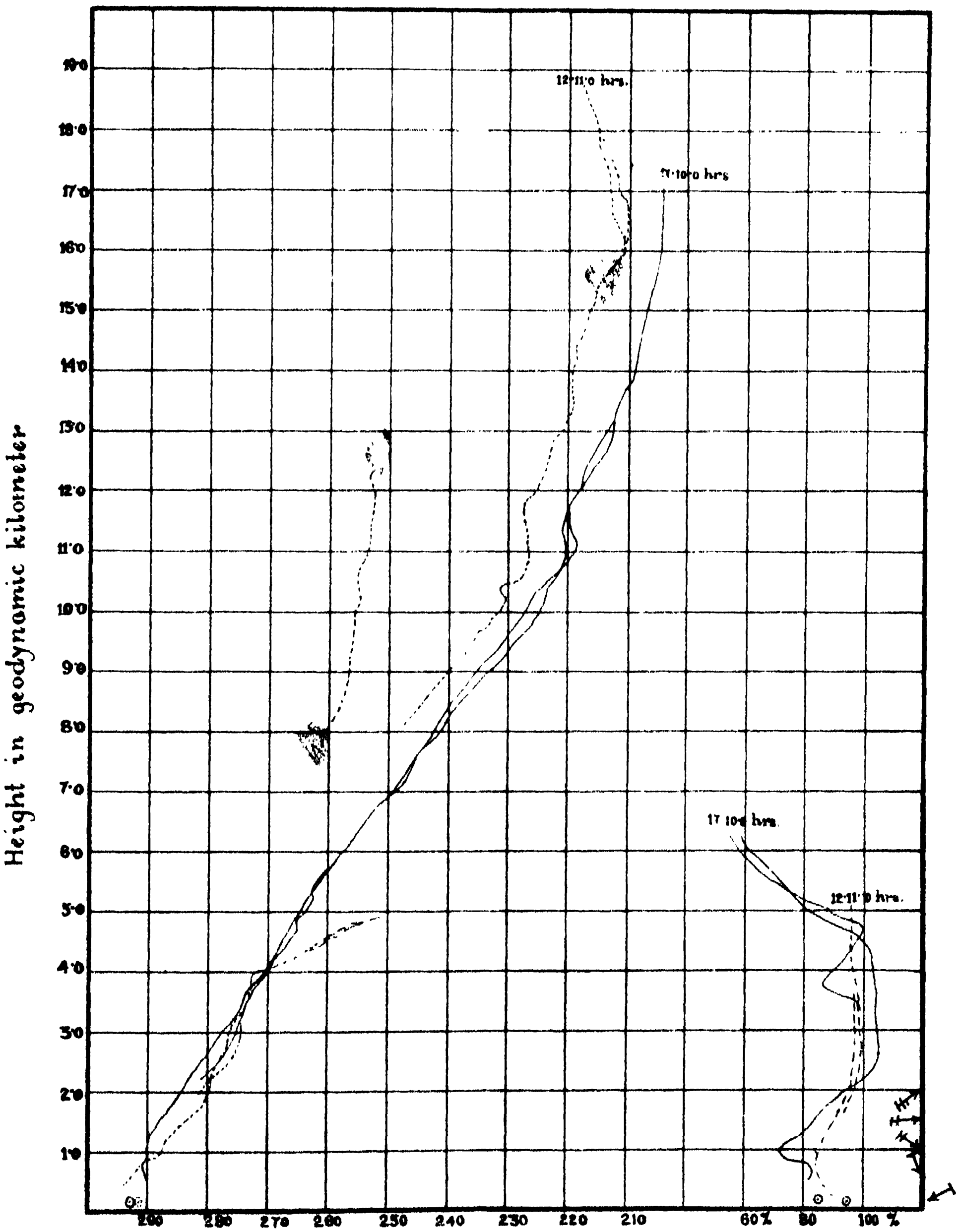


FIG. 8.

Plate VI

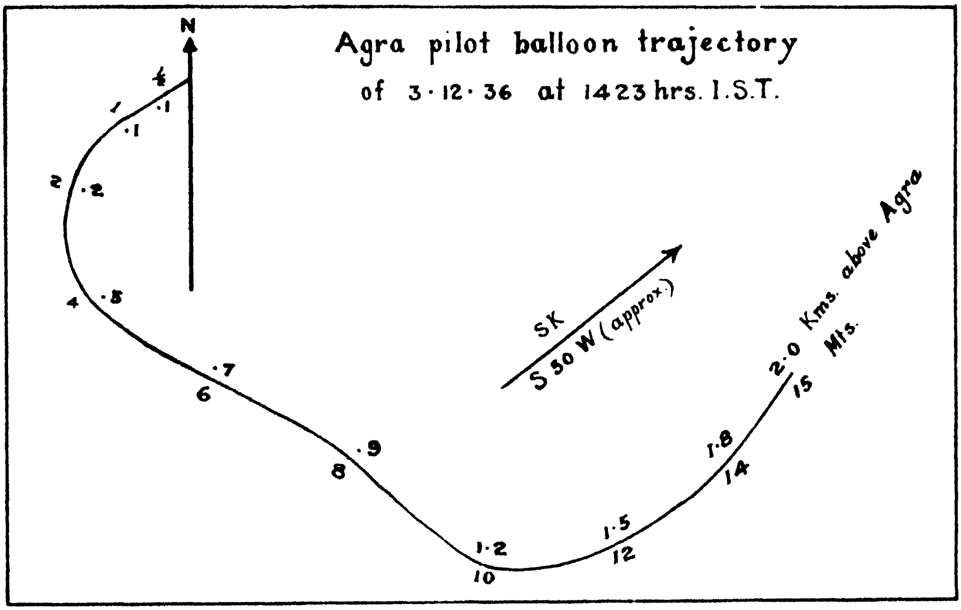


FIG. 9.

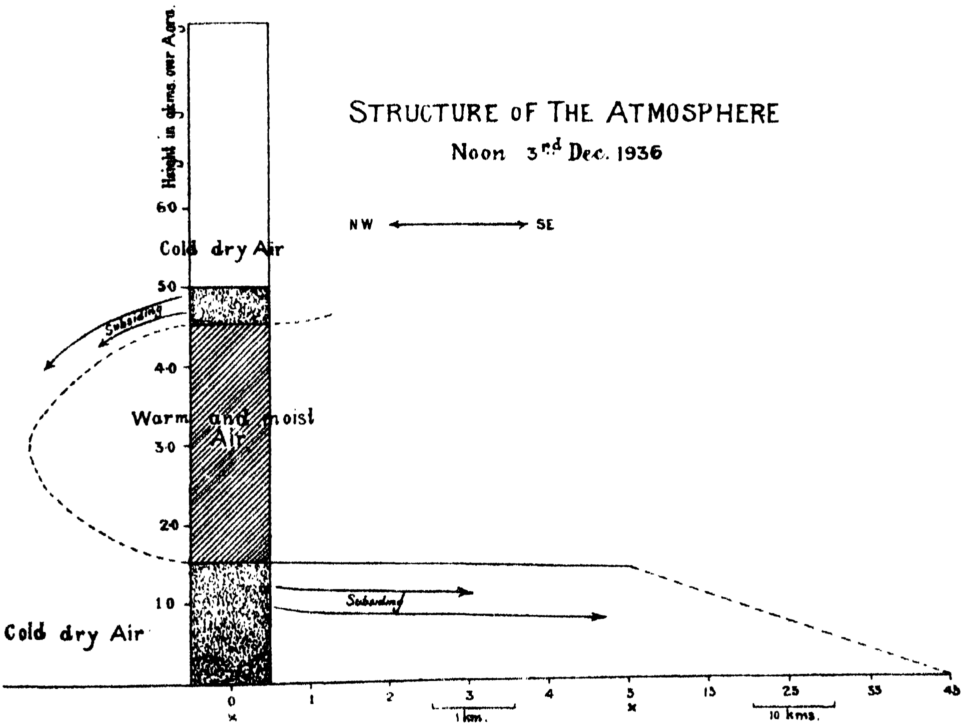


FIG. 10.

DGO. 19. VIII. 90
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Averages of Temperatures and Humidities in the upper air over Agra in the Polar year 1932-33.

BY

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551. 524·7 : 551.571·7.

AVERAGES OF TEMPERATURES AND HUMIDITIES IN THE UPPER AIR OVER AGRA IN THE POLAR YEAR 1932-33.

BY

S. BASU, RAM SAHAY AND K. J. KABRAJI.

(*Received on 8th December 1939.*)

Abstract.—The paper gives the averages of temperatures and humidities, over Agra, in the Polar Year (September 1932 to August 1933 inclusive) by months and by seasons, and attempts to explain the variations of these elements. Monthly and seasonal height/temperature and height/humidity diagrams have been given in the paper, with similar diagrams for individual ascents.

During the Polar Year September 1932 to August 1933, 80 sounding balloons carrying light self-recording meteorographs were let off from Agra. 45 of these were retrieved.[*]

The meteorographs used were all of the Dines type with the modifications that have been introduced by the India Meteorological Department, and were made at the Upper Air Observatory, Agra. They had a temperature scale double that of the original Dines type instrument; and in some the pressure scale was also doubled.[†] The meteorographs were aged by repeatedly taking them through a cycle of pressures at room temperature and at about -40°C., from surface atmospheric pressure to the anticipated lowest pressures. They were then calibrated at five temperatures ranging from that of the room to about -55°C.[‡] In calibrating for pressure, the lowest mark made on the record plate was for a pressure of about 30 mms. of mercury. The humidity scale was obtained by marking the plate at 0%, room humidity and 100%. A few hours before ascent a final-test mark was made on the plate keeping the instrument at a definite pressure below that of the atmosphere and at a definite temperature. This mark was used later to estimate the magnitude of any displacement of the calibration grid that might have occurred in the period of detention of the meteorograph after calibration and before final test on the day of flight. After the recovery of the meteorograph, its record was magnified about 50 times by optical projection and the image traced on paper. All further work was done on this trace.

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[*] For other upper air data collected during the Polar Year, see N. K. Sur and K. P. Ramakrishnan. Upper Air Temperatures and Humidities during the Polar Year—Part I. Aeroplane Ascents at Peshawar, Quetta and Karachi. Beitr. z. Phys. d. fr. Atmos., Vol. 24, pp. 199-204, 1937.

[†] G. Chatterjee. An Improved Method of sounding the Lower Layers of the Atmosphere. Ind. Met. Dep. Sci. Notes IV No. 35 (1931).

[‡] When the meteorographs were found to have recorded still lower temperatures aloft, these were evaluated by extrapolation. Special tests with a few instruments have shown the validity of extrapolation up to about -80°C.

In general, the records show two values of temperature and humidity for each pressure. Ordinarily the difference between the temperatures is less than 3°C., but in exceptional cases it reaches as much as 5°C. The humidity traces lie, in general, close to each other; but, when the humidity varies rapidly with height, the ascending and descending traces lie well apart from each other. The means of the two temperatures and humidities were taken for purposes of averaging.

To minimise vitiation of record by insolation, the ascents were generally made between 16 and 19 hrs. I. S. T. (G.M.T.+05·30 hrs). The rate of ascent of the balloon was generally in the neighbourhood of 15 km/hour.

The days for which meteorograph records were available in the Polar Year are given below according to months and seasons :—

Month.	Days for which records were retrieved.	Total number in month.	Season.	Seasonal total.
September 1932	3rd, 5th, 6th, 7th, 14th, 15th, 22nd	7	Post monsoon.	12
October ,,	13th, 24th, 26th, 27th, 28th	5		
November ,,	9th, 23rd, 29th, 30th	4	Winter	19
December ,,	10th, 15th, 20th, 21st, 22nd, 24th ..	6		
January 1933	5th, 11th, 12th, 25th, 26th	5		
February ,,	8th, 20th, 22nd, 24th	4		
March ,,	8th, 9th, 22nd, 23rd	4	Summer	10
April ,,	12th, 26th, 27th	3		
May ,,	12th, 25th, 26th	3		
June ,,	No ascent	..		
July ,,	12th	1	Monsoon	4
August ,,	10th, 25th, 29th	3		
	Total ..	45		

Tables of seasonal values IA, IB, IC and ID give, for the different levels, the monthly means of temperature (in °A) and of relative humidities (%). The temperatures have been rounded off to 0·5°A. The mean surface temperatures and surface humidities have been determined from the dry and wet bulb temperatures observed by an Assmann aspiration psychrometer, immediately before letting off the balloon.

RESULTS.

Table IA.

Post-Monsoon.

Level.	September 1932.				October 1932.			
	Temp.	No. of obsns.	Humidity.	No. of obsns.	Temp.	No. of obsns.	Humidity.	No. of obsns.
Surface	304·0	7	71	7	303·5	5	29	5
0·5 gkm.	301·0	5	79	4	302·0	3	36	2
1·0 "	297·0	7	84	7	297·0	5	37	5
1·5 "	293·5	7	92	7	293·0	5	40	5
2·0 "	291·0	7	90	7	288·5	5	44	5
2·5 "	288·0	7	88	7	284·0	5	50	5
3·0 "	286·5	7	83	7	280·0	5	54	5
4·0 "	282·0	7	73	7	277·5	5	46	4
5·0 "	275·5	7	73	7	271·0	5	54	3
6·0 "	271·0	7	66	7	266·0	5	51	4
7·0 "	265·5	7	67	7	260·5	5	45	4
8·0 "	259·5	6	63	6	253·5	5	44	5
9·0 "	252·0	6	66	6	246·0	5		
10·0 "	245·0	6	..	..	238·0	5		
11·0 "	237·0	6	..	..	230·5	5		
12·0 "	228·0	6	..	..	222·0	5		
13·0 "	219·0	6	..	..	213·0	5		
14·0 "	209·5	6	..	..	204·5	5		
15·0 "	200·5	6	..	..	197·5	5		
16·0 "	193·5	5	..	..	194·5	5		
17·0 "	190·0	5	..	..	197·5	5		
18·0 "	193·5	4	..	..	202·5	4		
19·0 "	..	..	..	..	207·5	3		

Temperatures from 2 gkm. to 15 gkm. for all the levels are lower by about 4°A in October than in September, but above 15 gkm. they are higher, the difference rapidly increasing with height. Humidities are lower in October than in September at all the levels; the difference being more marked at lower levels, up to about 3 gkm. This suggests that monsoon air occupied the country round about Agra up to 3 gkm. (in September) and that this air was replaced by drier air in October. A detailed discussion of the results of sounding balloon ascents on 3rd, 5th, 6th and 7th September 1932 has appeared in the India Meteorological Department Scientific Notes, Vol. VI, No. 65, by N. K. Sur.

TABLE IB.

Winter.

Level.	November 1932.				December 1932.			
	Temp.	No. of obsns.	Humidity.	No. of obsns.	Temp.	No. of obsns.	Humidity.	No. of obsns.
Surface	299·5	4	22	4	295·0	6	36	6
0·5 gkm.	297·0	3	33	2	291·5	2	47	3
1·0 „	292·0	4	37	3	289·0	6	50	6
1·5 „	289·0	4	37	3	287·0	6	50	6
2·0 „	286·5	4	34	3	284·0	6	53	6
2·5 „	285·0	4	30	3	281·0	6	54	6
3·0 „	283·0	4	27	3	278·5	6	52	6
4·0 „	277·0	4	26	3	271·5	6	57	6
5·0 „	270·0	4	27	3	265·0	6	58	6
6·0 „	263·0	4	27	3	259·5	5	51	5
7·0 „	256·5	4	27	3	252·5	5	50	5
8·0 „	249·0	4			244·0	4		
9·0 „	241·5	4			235·5	4		
10·0 „	234·5	4			227·0	4		
11·0 „	227·5	4			219·0	4		
12·0 „	220·5	4			212·5	4		
13·0 „	213·0	4			208·0	4		
14·0 „	207·0	4			205·5	4		
15·0 „	203·5	4			203·0	4		
16·0 „	199·0	4			202·5	4		
17·0 „	107·5	4			199·5	4		
18·0 „	198·5	3			200·5	4		
19·0 „					203·0	3		

TABLE IB—*contd.*

Winter.

Level.	January 1933.				February 1933.			
	Temp.	No. of obsns.	Humidity.	No. of obsns.	Temp.	No. of obsns.	Humidity.	No of obsns.
Surface	293·0	5	22	5	296·0	4	39	4
0·5 gkm	290·5	2	..	..	295·0	2	42	2
1·0 „	284·5	4	40	4	289·5	4	50	3
1·5 „	282·5	5	37	5	285·5	4	54	4
2·0 „	281·0	5	35	5	281·5	4	63	4
2·5 „	278·5	5	38	5	278·0	4	69	4
3·0 „	276·0	5	45	5	275·0	4	75	4
4·0 „	269·5	5	44	5	268·5	4	83	4
5·0 „	263·5	5	44	5	261·5	4	86	4
6·0 „	257·5	5	45	5	255·0	4	80	4
7·0 „	249·5	5	53	3	247·5	4		
8·0 „	243·0	5						
9·0 „	236·5	5						
10·0 „	230·0	5						
11·0 „	222·5	5						
12·0 „	210·0	3						
13·0 „								
14·0 „								
15·0 „								
16·0 „								
17·0 „								
18·0 „								
19·0 „								

In December temperatures at all levels up to 15 gkm. are lower than in November, but above 15 gkm. they are higher. January temperatures up to about 8 gkm. are lower than those for December, but from 8 gkm. to 11 gkm. they are higher, and above 11 gkm. there is an indication of these differences again changing sign. The differences between the January and February mean temperatures are not great, but a warming up of the lower layers in February can be seen. Humidities are higher in December than in November or January at practically all levels.

The apparent irregular variation of humidity from month to month in winter is due to the small number of observations.

TABLE IC.

Summer.

Level.	March 1933.				April 1933.				May 1933.				June 1933
	Temp.	No. of obsns.	Humidity.	No. of obsns.	Temp.	No. of obsns.	Humidity.	No. of obsns.	Temp.	No. of obsns.	Humidity.	No. of obsns.	
Surface ..	303·0	4	15	4	301·5	3	45	3	308·5	3	43	3	No ascent.
0·5 gkm ..	302·0	3	19	4	300·0	3	31	2	305·5	3	21	3	
1·0 " ..	295·5	4	18	4	297·5	3	47	3	300·5	3	27	3	
1·5 " ..	291·0	4	18	4	294·0	3	46	3	296·5	3	38	3	
2·0 " ..	286·0	4	19	4	289·5	3	47	3	293·0	3	55	3	
2·5 " ..	283·0	4	17	4	286·0	3	51	3	289·0	3	*60*	3	
3·0 " ..	279·5	4	19	4	281·0	3	59	3	286·0	3	47	3	
4·0 " ..	273·0	4	19	4	273·5	3	66	3	277·5	3	24	3	
5·0 " ..	265·0	4	21	4	267·0	3	68	3	271·5	3	20	3	
6·0 " ..	258·5	4	23	4	259·5	2			265·0	3	18	3	
7·0 " ..	252·5	3	26	3	253·0	2			260·5	3	23	3	
8·0 " ..	246·0	3			246·5	3			254·5	3			
9·0 " ..					237·5	3			247·0	3			
10·0 " ..					229·0	3			240·0	3			
11·0 " ..					222·5	..			233·0	3			
12·0 " ..					218·5	3			226·0	3			
13·0 " ..					213·5	3			217·5	3			
14·0 " ..									209·0	3			
15·0 " ..									201·5	3			
16·0 " ..									195·5	3			
17·0 " ..									192·0	3			
18·0 " ..									192·0	3			
19·0 " ..									199·0	3			
20·0 " ..													

In May the temperatures are higher than in April for all levels for which means are available, *i.e.*, upto 13 gkm. Humidities are lowest in March, which is also the driest month in the Polar Year.

Where means of temperature are available for sufficiently great heights, the tropopause is seen to be between 16 and 19 gkm. (In the monsoon no data up to these heights are available; retrieved meteorographs being very few in that season, only a general idea of the tropopause can be gained from the individual ascents, shown in *Fig. 6*).

TABLE ID.

Monsoon.

August 1933.

Level.	Temperature.	No. of observations.	Humidity.	No. of observations.
Surface.	301·5	3	86	3
0·5 gkm.	300·0	3	95	1
1·0 „	296·5	3	91	3
1·5 „	293·5	3	92	3
2·0 „	290·5	3	91	3
2·5 „	288·5	3	91	3

Much cannot be deduced from the data collected for the monsoon months, because of the small number of retrieved balloons.

Fig. 1 shows the monthly average height/temperature and height/humidity graphs.

In *Table II* the average temperatures and humidities have been given by seasons and for the year. The monsoon averages have however been determined from only 4 meteorograph records. It is in that season however that the coldest tropopauses have been observed.

TABLE II.

Level.	Post monsoon season.		Winter season.		Summer season.		Monsoon season.		Annual.		Level.
	Temp.	Humidity.	Temp.	Humidity.	Temp.	Humidity.	Temp.	Humidity.	Temp.	Humidity.	
Surface.	304·0	49	296·0	30	304·5	34	304·0	75	301·0	47	Surface.
Gkm—.											Gkm.—
0·5	301·5	57	293·5	41	302·5	24	300·0	95	298·5	54	0·5
1·0	297·0	61	288·5	44	298·0	31	298·0	91	294·5	57	1·0
1·5	293·0	66	286·0	45	294·0	34	294·5	87	291·0	58	1·5
2·0	289·5	67	283·5	46	289·5	40	292·0	83	288·0	59	2·0
2·5	286·0	69	280·5	48	286·0	43	289·0	85	284·5	61	2·5
3·0	283·5	69	278·0	50	282·0	42	286·5	85	281·5	62	3·0
4·0	279·5	59	271·5	53	275·0	36	281·5	81	275·5	57	4·0
5·0	273·5	63	265·0	54	268·0	36	277·5	63	269·5	54	5·0
6·0	268·5	59	259·0	51	261·0	37	271·0	58	263·5	51	6·0
7·0	263·0	56	251·5	43	255·5	39	265·5	58	257·0	49	7·0
8·0	256·5	53	244·5		249·0	15	259·5	73	250·5		8·0
9·0	249·0	66	237·0		241·0	13	251·5	63	243·0		9·0
10·0	241·5		229·5		234·0		244·5		235·5		10·0
11·0	234·0		221·5		228·5		236·0		228·5		11·0
12·0	225·0		215·0		222·5		227·0		221·0		12·0
13·0	216·0		209·5		215·5		218·0		214·0		13·0
14·0	207·0		206·5		209·5		208·5		207·5		14·0
15·0	199·0		204·5		203·0		200·5		202·5		15·0
16·0	194·0		202·5		198·0		193·5		198·0		16·0
17·0	193·5		200·5		195·5		189·0		196·0		17·0
18·0	198·0		199·5		196·5		192·5		197·0		18·0
19·0	204·5		201·5		200·0		192·0		200·5		19·0
20·0											20·0

Fig 2 gives the seasonal height/temperature and height/humidity curves.

As the data of some of the individual traces were omitted entirely or in part from the above averages because there were not sufficient of them in their month or sufficient going up to high enough levels, it has been thought advisable to reproduce their geodynamic-height/temperature and geodynamic-height/humidity graphs in *Figs. 3—6.*

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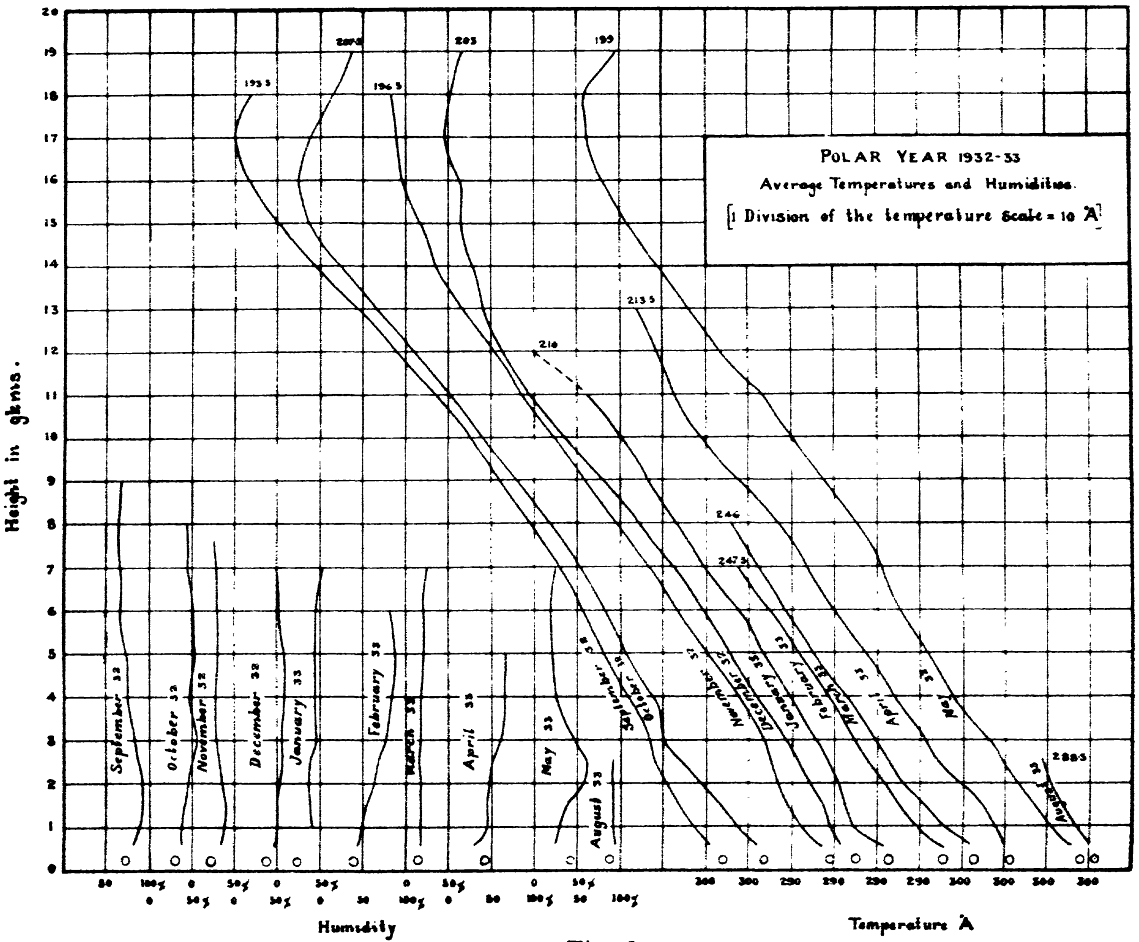


FIG. 1.

G P. Z. D POONA, 1940.

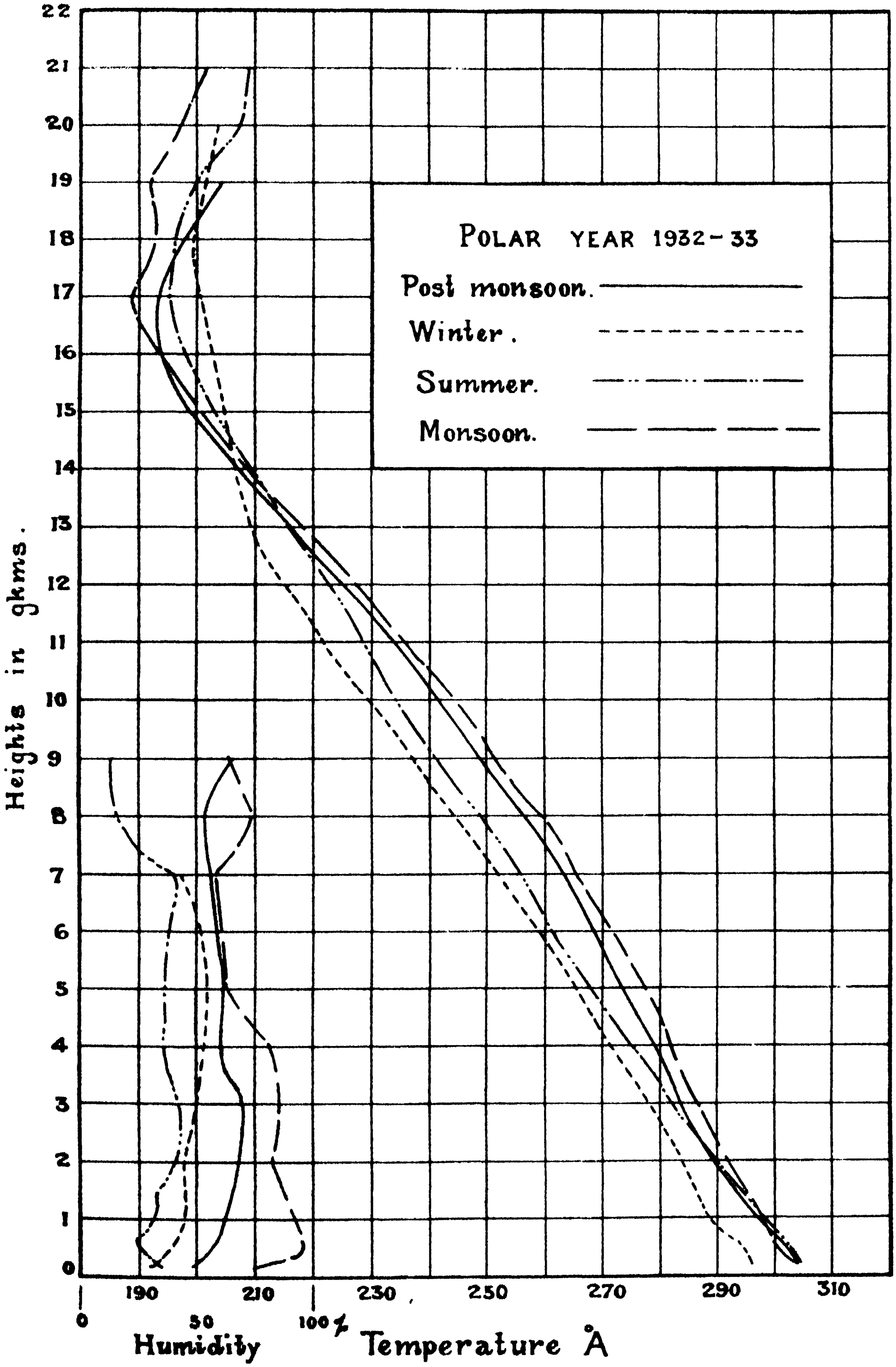


FIG. 2.

G. P. I. D. POONA, 1940.

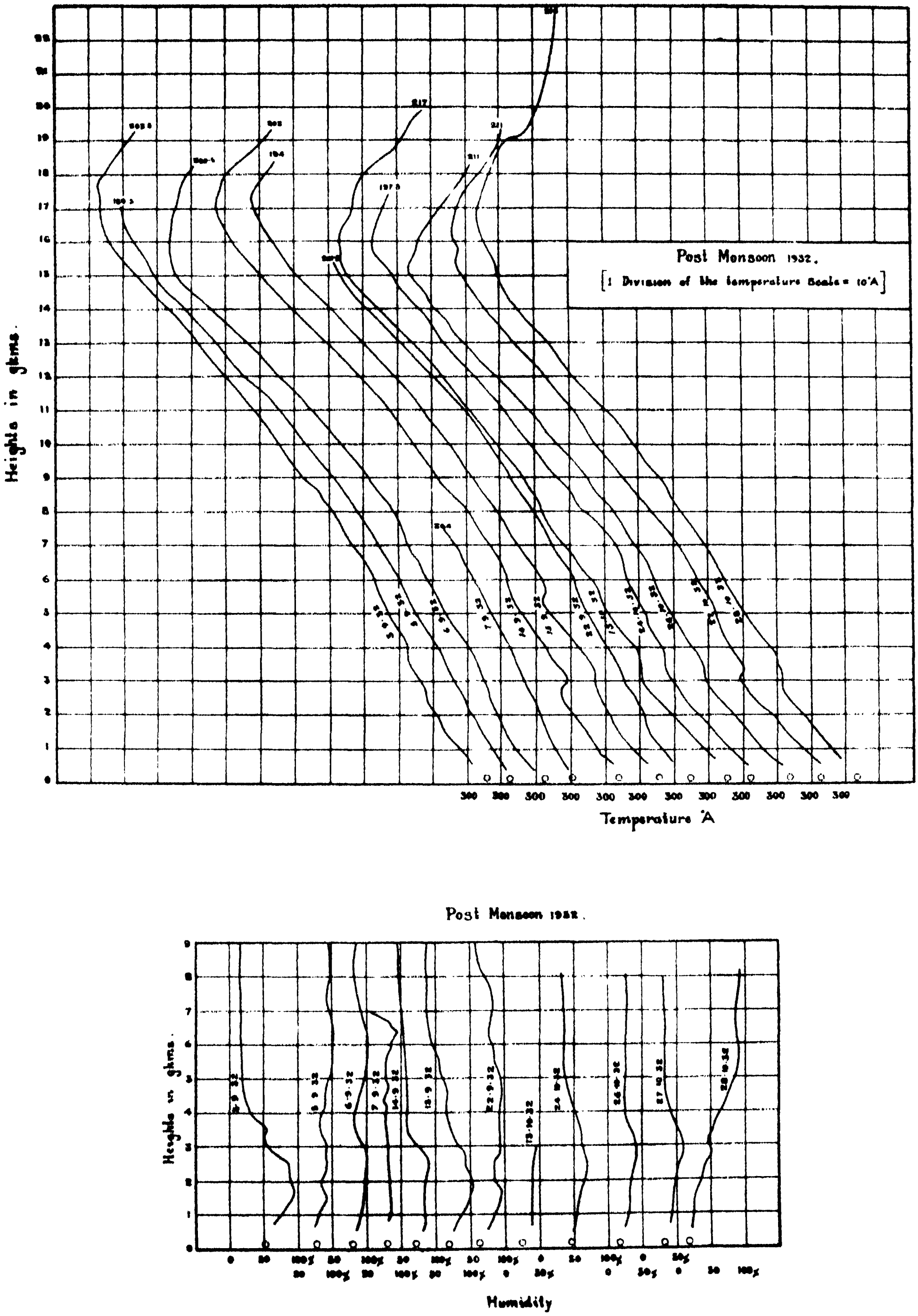
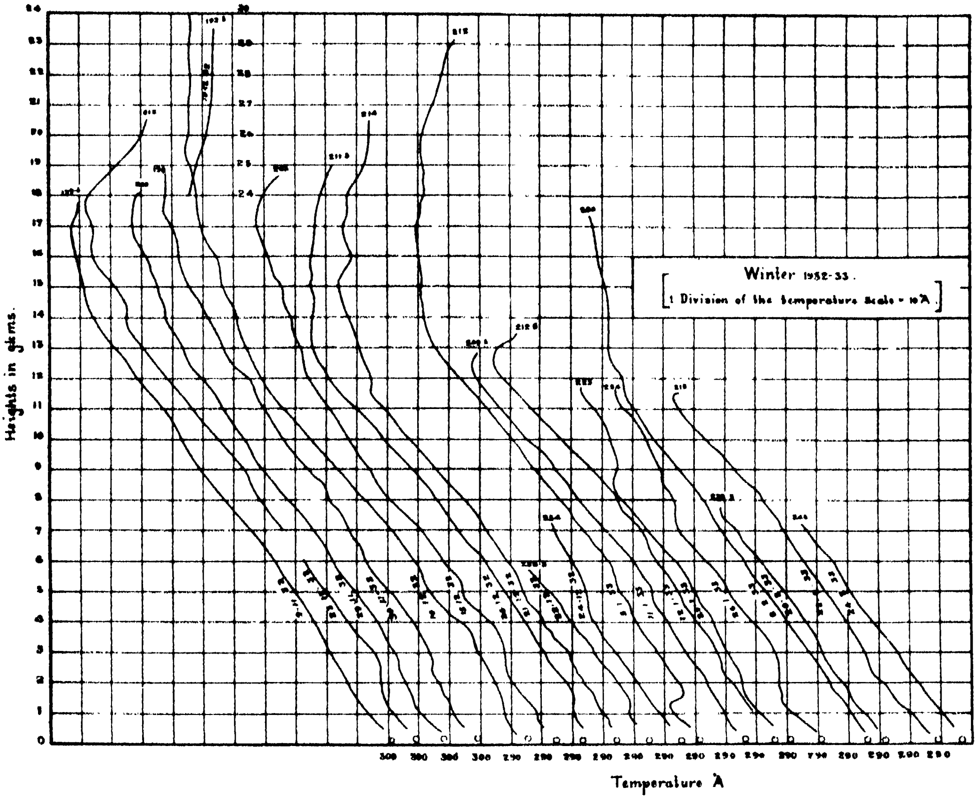


Fig. 3.

G P Z O POONA, 1940



Winter 1932-33.

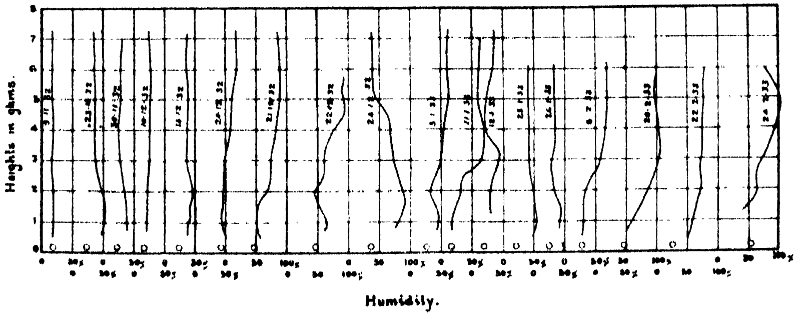


FIG. 4.

G P Z.B. POONA, 1948

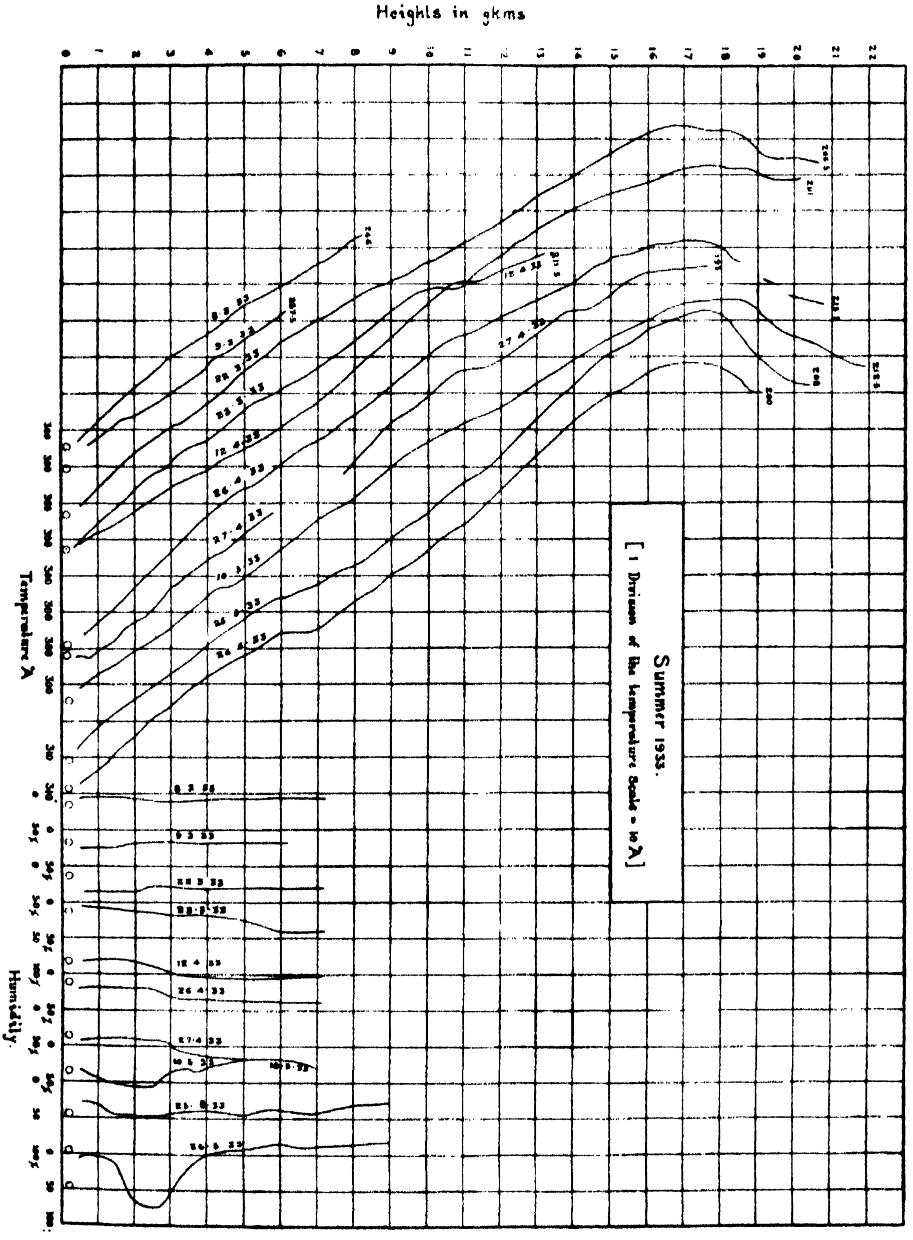


FIG. 5.

G P Z O POONA. 1940.

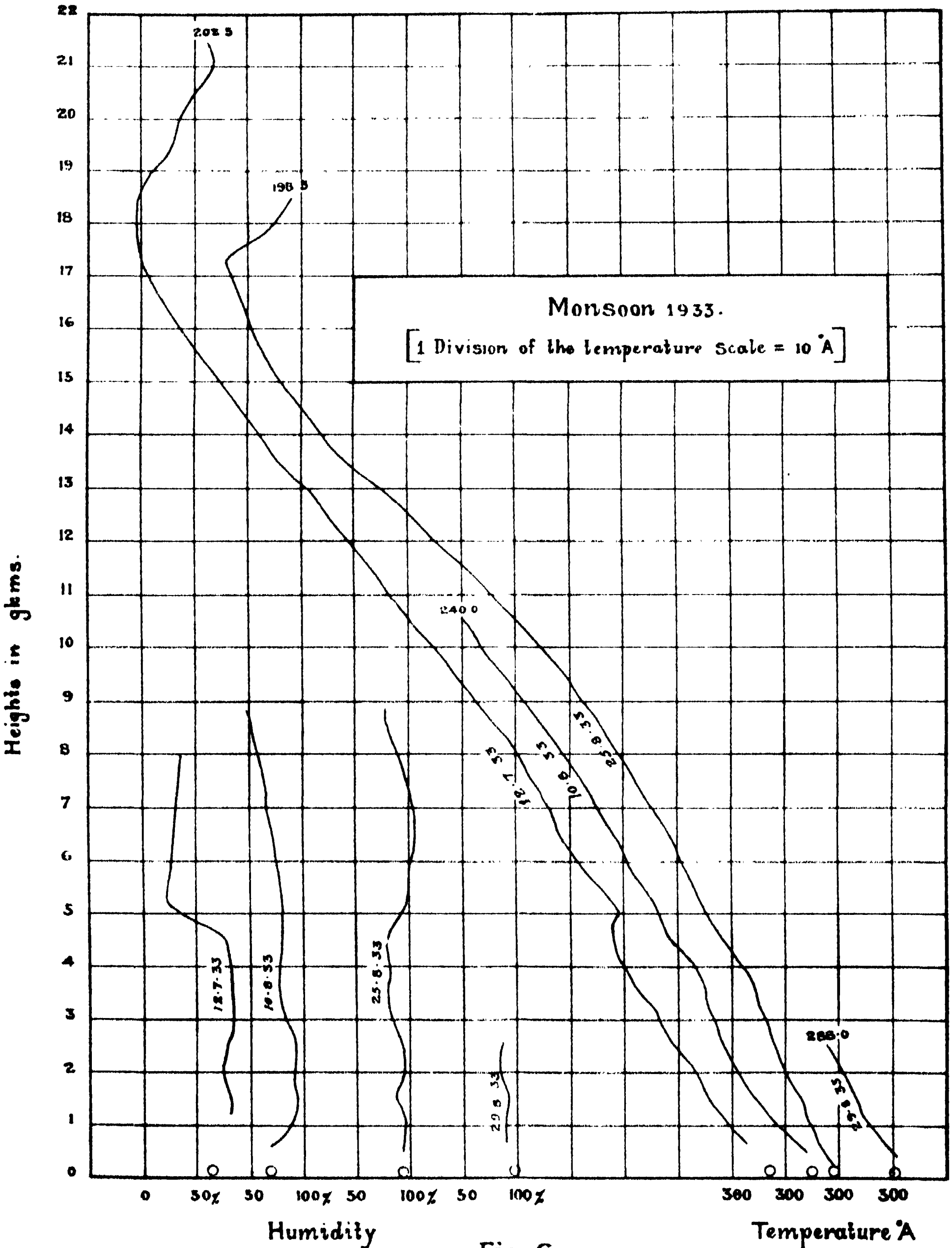


Fig. 6.

G. P. I. O. POONA, 1940.

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INDIA METEOROLOGICAL DEPARTMENT

SCIENTIFIC NOTES

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The Hindu Kush Earthquake of November 21, 1939.

BY

S. M. MUKHERJEE and A. R. PILLAI.
Colaba Observatory, Bombay.

(Received on 22nd May 1940.)

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THE HINDU KUSH EARTHQUAKE OF NOVEMBER 21, 1939.

BY

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(*Received on 22nd May 1940.*)

Abstract.—The epicentre of the earthquake of November 21, 1939, is obtained as 36°11′N. and 70°53′E., in the Hindu Kush. The depth of focus as determined is 210 ± 14 km., and the hypocentral time 11h. 01m. 43s. G.M.T. The various characteristics observed in respect of this shock are discussed and are found to be essentially similar to those of the previous deep ones from the same region. The possibility of getting useful information regarding the origin of these shocks from a careful study of their seismograms obtainable at a single Indian station is pointed out. It is found that strong shocks occur generally in winter and weak ones in all the seasons. Frequency of occurrence of both the classes is two per year. The phase *sP* is specially strong in the Indian seismograms being recorded at 8°, the smallest epicentral distance at which seismograms were available for this study.

The earthquake occurred at 16h. 30m. I.S.T., in the Hindu Kush This is one of the strongest of the deep-focus shocks which have originated in that region in recent years and as on previous occasions was felt with varying intensities practically over the whole of the North-West Frontier Province, Kashmir and Jammu State, the north Punjab and Afghanistan. At Gilgit, Drosh and Srinagar in the Kashmir State, the intensity of the shock reached nearly 9 on the *R*—*F* scale. So far as available reports indicate, Lahore appears to be the farthest place from the epicentre to experience the shock.

An examination has shown that the seismograms of deep shocks from the Hindu Kush as registered at Bombay are characteristically similar to one another. In the north component for instance, *sP* is recorded very conspicuously and its amplitude is as large as that of *P*. The first direction of both is towards the South. The time interval *sP*—*P* is nearly one minute. *S* begins with a small impulse and in a few seconds attains its maximum amplitude, which is somewhat larger than that of *P* and is the largest in the seismograms. Although the surface waves are poor, *L* and *M* can be recognised. Some of the waves reflected from the outer boundary of the core, direct, or after reflection near the epicentre as a consequence of the depth, are also identifiable. First longitudinal movements in N—S and E—W components give the azimuth of the epicentre from Bombay near about 5 degrees east of north, and this is very near the correct value. All the shocks examined are found to have been recorded with initial compression at Bombay as at the European stations. These common features are so conspicuously repeated in nearly every case, that it becomes easy to get reliable information as to the origin of these shocks even from a general visual examination of the Bombay seismograms. The N—S component of the Milne-Shaw seismogram of the earthquake of November 21, 1939, reproduced in *Fig. 1* (*b*) is a typical illustration of these features.

From Bombay seismograms, supplemented by readings obtained telegraphically from Agra, Calcutta and Kodaikanal, the epicentre of the shock of November 21, 1939 was tentatively located at 36°·5N. and 70°·5E. The depth and hypocentral time were obtained as 200 km., and 11h. 01m. 40s. G.M.T. respectively. The United States Coast and Geodetic Survey determinations based on data from 8 stations are as follows : 10°N. and 60°E ; 200 km. and 11h. 1·2m. G.M.T. However, after using more data from European and Pacific stations, U.S.C.G.S., gives the revised values as 35°N. and 71°E., 11h. 01m. 33s. with no change in depth. These revised values are close to those obtained by Bombay.

Accurate determinations of the epicentres and depths of the Hindu Kush shocks, as and when they might occur, are of great interest for comparison of the characteristics of these shocks with those of the previous ones from the same region. It is important to enquire whether there are any systematic changes of position of the epicentres or of depths of these shocks. In the present examination, seismograms from 5 Indian stations and Colombo, and readings from 32 extra-Indian stations have been used. These stations are fairly representative of the different azimuths of the epicentre and the quality of material available appears to be sufficiently good for a satisfactory location of the position of the epicentre. From a comparison of different trial positions, the best approximation to the epicentre of the shock of November 21, 1939, is 36°·1N. and 70°·8E. In *Table I* are given the results of comparison of four of the positions tried, namely, (1) the revised epicentre determined by the U.S.C.G.S., (2) the preliminary epicentre given by Bombay, (3) one trial position very near the best approximate position and (4) the best approximate position. From Geiger's method of least squares solution, the probable

TABLE I.

Station.	P (Observed).	(1) 35°N., 71° E. 11h. 1m. 43s.		(2) 36°·5N., 70°·5E. 11h. 1m. 43s.		(3) 35°·9N., 70°·7E. 11h. 1m. 43s.		(4) 36°·1N., 70°·8E. 11h. 1m. 43s.	
		Δ	O—C.	Δ	O—C.	Δ	O—C.	Δ	O—C.
	H. M. S.	°	s.	°	s.	°	s.	°	s.
Bombay ..	*i* 11 5 36	16·2	+15	17·2	—3	17·1	+4	17·3	+2
Kodaikanal	*i* 7 07	25·5	+9	27·0	—5	26·4	0	26·5	0
Colombo ..	*i* 7 41	29·3	+9	30·8	—4	30·2	+1	30·3	0
Hong Kong	9 01	39·6	+2	40·2	—3	40·0	—2	39·6	0
Chur ..	*i* 9 40	46·7	—6	46·1	—2	46·0	—1	45·9	—1
Uccle ..	*i* 10 11	49·5	—5	48·2	+4	48·7	+1	48·7	+1
Manila ..	*i* 10 16	49·9	—3	49·8	—3	49·6	—1	49·5	—1
Paris ..	*i* 10 22	51·0	—5	49·8	+3	50·3	0	50·2	+1
Kew ..	*i* 10 30	52·3	—7	51·0	+3	51·5	—1	51·4	—1
Toledo ..	*i* 11 14	58·0	—3	57·0	+3	57·3	+1	57·3	+2
Weston ..	*i* 14 42	95·3	—5	93·8	+2	94·4	—1	94·3	0
Fordham ..	*i* 14 53	97·6	—4	96·0	+3	96·7	—2	96·5	+1
Pittsburg ..	*i* 15 02	99·9	—6	98·4	+1	99·0	—1	98·9	0
Pasadena	*e* 15 48	110·3	—7	108·9	+1	109·5	—2	109·3	0

corrections to the best approximate position given above are obtained as $d\phi = +5'$ and $d\gamma = +5'$. The finally accepted position of the epicentre is 36°11'N. and 70°53'E. In these calculations, *P* readings from 8 stations representative of the different directions of the epicentre and Gutenberg and Richter's tables[2] were used. The *P*-residuals for all the stations with respect to the corrected position 36° 11'N. and 70° 53'E., using both Gutenberg and Richter's and Jeffreys' tables[3]

TABLE II.

Epicentre: 36°11'N., 70°53'E.

Station.	Δ	A O—C.	B O—C.	Station.	Δ	A O—C.	B O—C.
	°	s.	s.		°	s.	s.
Dehra Dun ..	8·4	+13	+13	Uccle ..	48·6	+1	+1
Agra ..	10·9	+1	+4	Manila ..	49·5	0	0
Bombay ..	17·4	+1	—2	Paris ..	50·2	+1	0
Calcutta ..	20·4	+2	+3	Clermont Ferrand.	50·6	+60	+60
Kodaikanal ..	26·6	0	0	Kew ..	51·4	—1	—1
Ksara ..	28·6	+3	+3	Jersey ..	53·0	—2	—2
Colombo ..	30·4	0	0	Alger ..	53·3	+1	+1
Helwan ..	33·5	+1	+1	Alicante ..	55·5	0	—1
Bucharest ..	34·7	+2	+2	Toledo ..	57·3	+1	0
Hong Kong ..	39·9	0	0	Granada ..	58·1	—1	—2
Trieste ..	43·3	—1	—1	Malaga ..	58·9	—1	—3
Prato ..	45·4	—1	0	San Fernado.	60·3	0	—1
Chur ..	45·9	0	—1	Coimbra ..	60·8	+1	0
Zurich ..	46·5	—2	—2	Ottawa ..	93·6	—1	—1
Strasbourg ..	46·8	+2	+2	Weston ..	94·2	0	+1
Basel ..	47·1	0	0	Fordham	96·5	+1	+1
Neuchatel ..	47·7	+1	0	Pittsburg	98·8	0	0
De Bilt ..	47·9	+2	+2	Pasadena	109·1	0	
Besancon ..	48·2	+2	+2				

A.—*P*-residuals obtained with Gutenberg and Richter's Tables and origin time 11h. 01m. 43s.
B.—*P*-residuals obtained with Jeffreys' Tables and origin time 11h. 01m. 49s.

are given in columns A and B of *Table II*. The difference of 6 secs. in the time of origin of the shock according to the two tables is to be noted. The time 11h. 01m. 43s. according to the first table is the hypocentral origin time of the shock. That calculated from the formula O=pP+P/2—tp—C is 11h. 01m. 42±3s. The depth adopted is 210±14 km. The values according to different phases are given in *Table III*. It is found that the present epicentre is very close to the old positions but does not coincide with any of them. The depth agrees well with those observed in the cases of previous shocks[4].

TABLE III.

pP—P.	*sP—P.*	*sS—S.*	*sScS—ScS.*	Mean.
218±17	206±11	207±6	200	210±14

In and around India, there are two principal regions where deep shocks occur. In Assam and Burma, the depths vary between 60 and 130 km.[1,4b] The other region is the Hindu Kush. Here the shocks exhibit certain peculiarities which appear to be unique in many respects. The distribution of their epicentres is restricted to a very small area round about the position 36°·5N. and 70°·5E., from which position alone 22 shocks are reported to have occurred during the past 20 years. The depths of these shocks are found to range by about 30 km. on either side of 210 km. With the aid of the International Seismological Summary, Gutenberg and Richter's lists of deep-focus earthquakes, seismological and non-instrumental observations published by the India Meteorological Department and seismograms obtained at the Colaba Observatory, monthly frequency distribution of deep-focus earthquakes in the Hindu Kush during the years 1921—39 has been found to be as follows :—

TABLE IV.

Nature of the shock.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sep.	Oct.	Nov.	Dec.	Total.
Weak ..	4	1	2	3	3	2	2	2	2	3	1	1	26
Moderately strong.	1	..	..	..	1	..	..	..	..	2	1	1	6
Strong ..	1	1	..	..	..	..	..	..	..	..	3	1	6
Total ..	6	2	2	3	4	2	2	2	2	5	5	3	38

These refer to those earthquakes for which co-ordinates of epicentres and depths were available. It will be seen from the table that they occurred at the rate of two per year. From 1929 onwards the seismic activity in the Hindu Kush region seems to have been on the increase and a strong or moderately strong earthquake occurred almost every year. The six strong and three moderate earthquakes occurred in the winter months from November to February and of the remaining three moderate earthquakes two were in October and one in May. The weak ones of course occurred in all the months of the year. It should, however, be mentioned that the classification of these earthquakes according to intensity is not based on any definite scale and the data available for this purpose are not very homogeneous. It is interesting to note that many of the Hindu Kush shocks under review have provided much valuable material for the study of several investigators[5].

A few selected seismograms from some of the Indian stations and Colombo are reproduced in *Fig. 1* (a, b, c, d). According to Gutenberg and Richter, *sP* is expected to be recorded from about 20° of epicentral distance[2]. In the present case, however, *sP* is very clearly recorded at Delhra Dun ($\triangle=8^{\circ}\cdot4$) *Fig.* 1 (*a*) and Agra ($\triangle=10^{\circ}\cdot9$). A review of the past records of the Hindu Kush shocks at these stations shows that this phase was recorded also on previous occasions but misidentified as P^* or *S* etc. In the present instance, Dehra Dun read *S* for *sP* and *L* for *S* in the preliminary tabulations. The time intervals *sP—P* from Dehra Dun and Agra give fairly the correct value of the depth of the present shock according to the tables of Wadati and Masuda[6] At Colombo and Calcutta also *sP* is very clear. *Fig. 1* (c and d). *pP* is recorded at Kodaikanal ($\triangle=26^{\circ}\cdot6$) and very clearly at Colombo ($\triangle=30^{\circ}\cdot4$). At Bombay ($\triangle=17^{\circ}\cdot4$) and Calcutta ($\triangle=20^{\circ}\cdot4$) some minor changes are observed at about the time when *pP* is expected to arrive. It may be noticed in the E—W component at Colombo that *S* is rather indefinitely recorded as an isolated movement and consequently *sS*, which is very clear, was read as *S* by Colombo in the first tabulations. *sS* is also clear at Calcutta. *ScS* and *sScS* are recorded on these seismograms. *sPcP* at Bombay and Calcutta and *PcS* at Calcutta and Colombo are recorded with large amplitudes.

It may be mentioned that the increased time-scale (15mm/min.) recently introduced in the Milne-Shaw N—S component at Colaba gives much greater ease and certainty in reading times of incidences of the phases as compared to the old time scale (8mm/min.). It is however considered that even more open time-scale (not less than 30 mm/min. and preferably 60 mm/min.) in the recording of the more sensitive seismographs would be desirable for useful study of these shocks at epicentral distances of 10° and less. Separation of the phases is well shown in Calcutta Omori-Ewing seismograms which has a time-scale of about 26 mm/min.

Conclusion.—By Geiger's method of least squares solution the epicentre of the earthquake of November 21, 1939, is obtained as 36°11′N. and 70°53′E. The depth is calculated as 210±14 km. The hypocentral time is obtained as 11h. 01m. 43s. G.M.T. The tendency of the Hindu Kush shocks to originate from very near the same focus as reported by previous observers is confirmed by these observations. This shock, like the previous ones, was recorded with initial compression at Bombay and at the European stations. The seismograms recorded at Bombay closely resemble those of the previous deep shocks from the Hindu Kush region. Strong shocks from the Hindu Kush exhibit a tendency to occur in winter and weak ones in all the seasons. The frequency of occurrence of both the classes is two per year These observations suggest that the topography of the Hindu Kush plays some part in the production of these shocks. The stresses responsible for them apparently accumulate at the focus at a depth of about 200 to 250 km. from the surface and are released probably by the same mechanism in every case. *sP* is clearly recorded at about 8°, the smallest epicentral distance at which seismograms were available. A careful study of the characteristics of the Hindu Kush shocks and the phase *sP* in the Indian seismograms suggests the possibility of affording very reliable information regarding the epicentre and depth of these shocks from the seismograms of a single Indian station. The desirability of more open time-scales is suggested.

Our thanks are due to the Directors of Observatories who sent us their seismograms. We are grateful to Dr. S. R. Savur, for his encouraging help.

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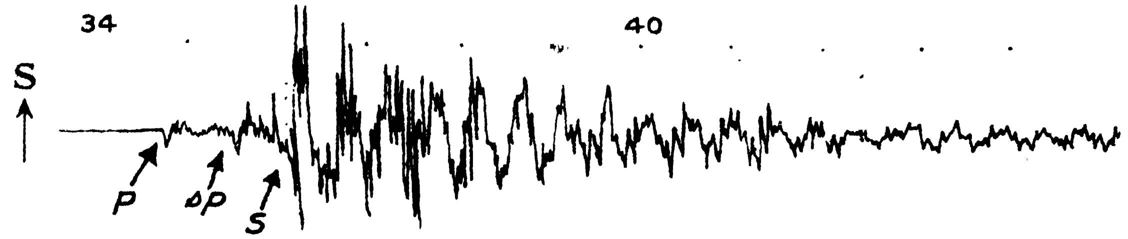

Fig. 1(a). Dehra Dun. Δ = 8°·4

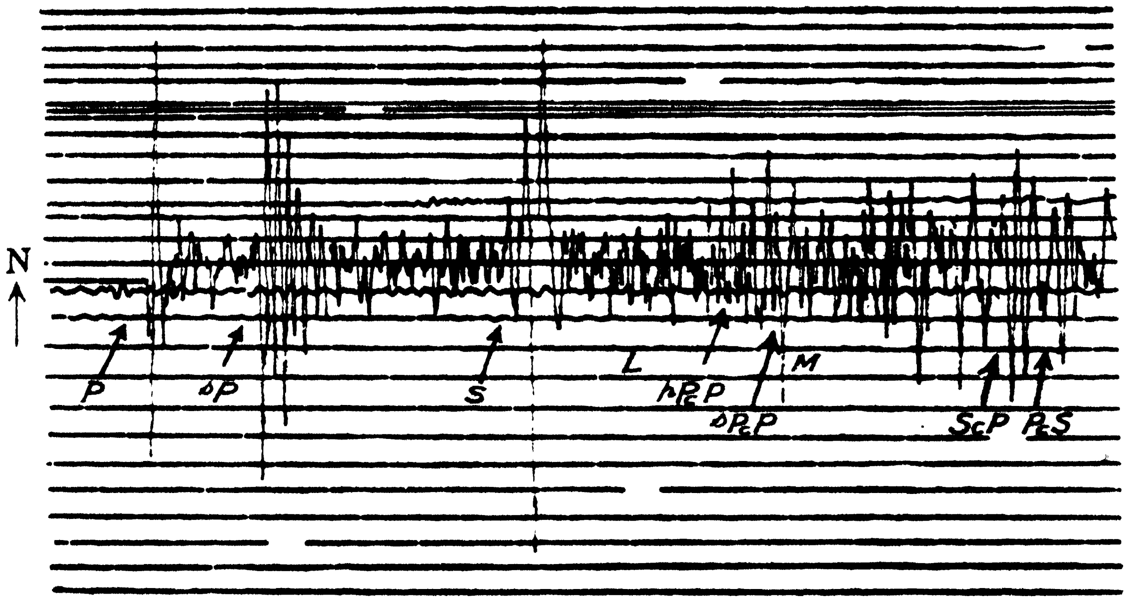

Fig. 1(b). Bombay. Δ = 17°·4

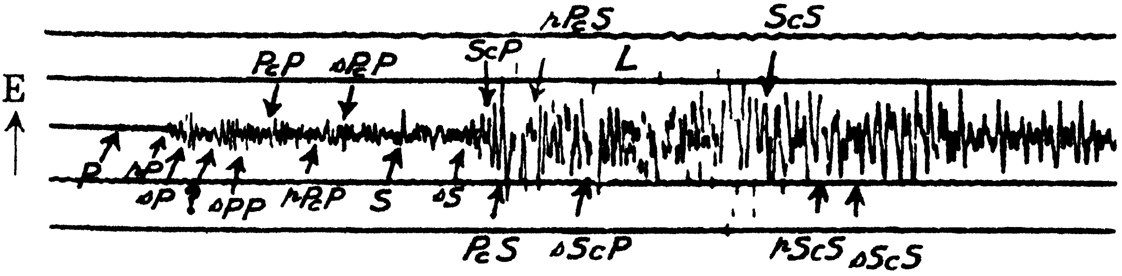

Fig. 1(c). Colombo. Δ = 30°·4

Seismograms of the Hindukush Earthquake of November 21, 1939.

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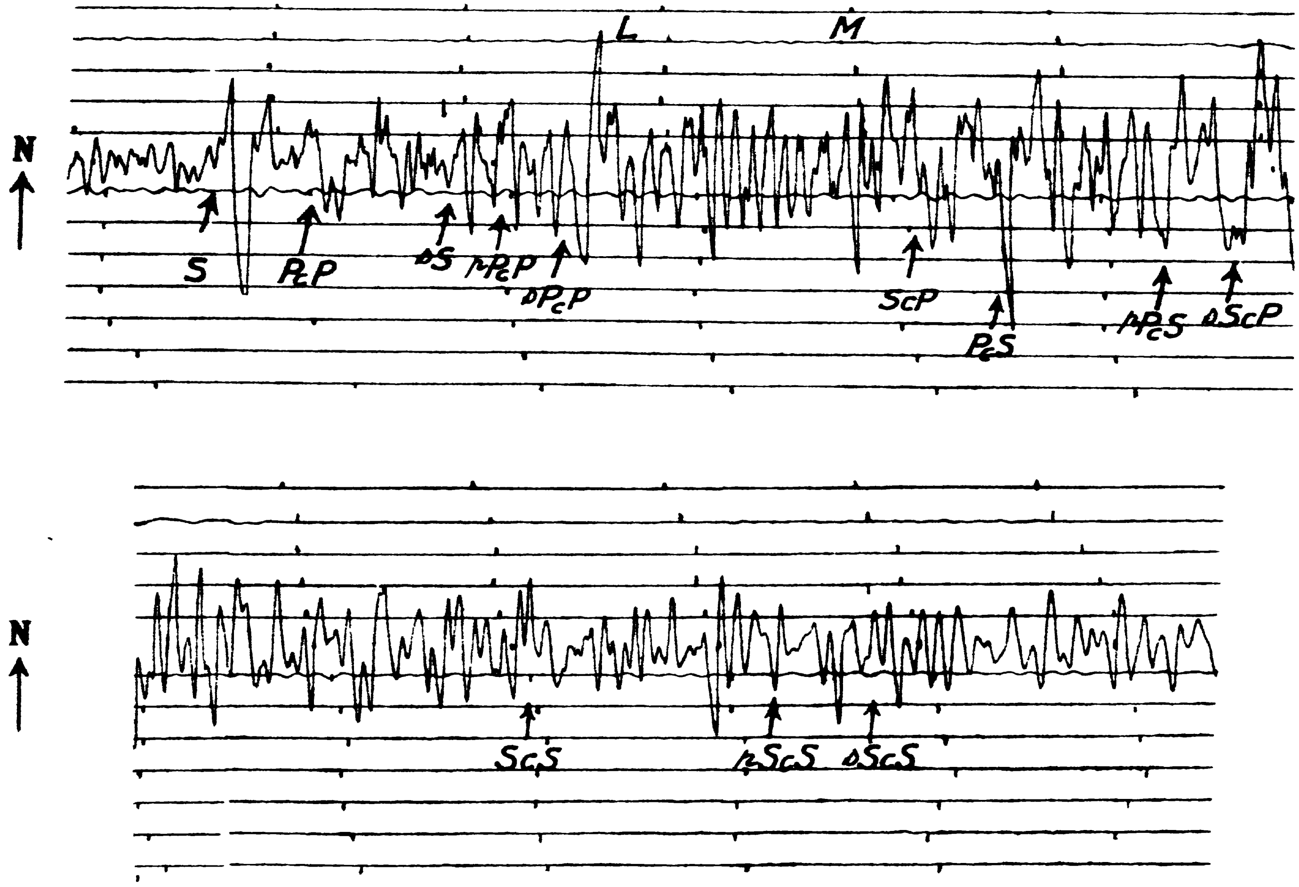

Fig. 1(d). Calcutta. Δ = 20°.4.

Seismograms of the Hindukush Earthquake of November 21, 1939.

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SCIENTIFIC NOTES

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Correlation between Frost and the preceding Meteorological Conditions—Part II—(Jaipur)

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CORRELATION BETWEEN FROST AND THE PRECEDING METEOROLOGICAL CONDITIONS—PART II—(Jaipur).

BY

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Abstract.—Observations made at 1600 hrs. (local time) at Jaipur during the period 1918-1929 have been analysed statistically and equations developed between the minimum temperature reached during the night and the dew point, dry bulb, wet bulb and maximum temperatures on the preceding afternoon. The physical significance of these statistical equations is discussed. The observed and calculated values of minimum temperature agree closely in over 94 per cent. cases. The discrepancies in the remaining 5 or 6 per cent. cases are generally not large and the causes producing these are discussed. Conditions most favourable for the occurrence of frost at the station are stated. The present paper confirms the result brought out by the previous paper, in which the data of Lahore were analysed, that for the forecasting of minimum temperature the single factor, wet bulb temperature, is as good as many dual combinations of functions of temperature and vapour pressure.

Introduction.

In a previous paper[1] [1931] on the subject, the authors discussed the temperature data of the meteorological observatory at Lahore and developed equations statistically, expressing the minimum temperature reached during the night in terms of the dew point, dry bulb and wet bulb temperatures as recorded at the observatory at 16 hrs. local time on the preceding afternoon. In view of the importance of forecasts of minimum temperature to agriculturists, the need of determining the constants in similar formulæ for other representative stations in India was emphasised in that paper. Most of the computational work involved in the present paper, in which the temperature data of the meteorological observatory at Jaipur have been discussed, was completed some years ago, but owing to the occupation of the authors in other directions, the investigation could not be completed till now. Mr. Narasimhan and Dr. L. A. Ramdas[2] [1937] have computed the values of the statistical constants in an equation expressing minimum temperature in terms of the maximum temperature and the vapour pressure of the air recorded on the preceding afternoon for a number of stations in India, and have, thereby, met to a large extent the needs of the agricultural interests in the matter. The equation derived by the above authors is a variation in form of one expressing minimum temperature directly in terms of dry bulb and wet bulb temperatures recorded on the preceding afternoon, since vapour pressure is not observed directly but has to be computed from the values of the dry bulb and wet bulb temperatures by means of the usual psychrometric tables, and the difference, on clear days, between the maximum temperature and the dry bulb temperature, recorded at the observatories of the India Meteorological Department in the afternoon, is usually small.

Jaipur lies in latitude 26° 55′N and longitude 75° 52′E and is about 1,431ft. above mean sea level. The meteorological observatory is about 1⅜ miles to the west of the city; the latter stands on a small plain or in a basin which is considered to have been the bed of a lake. On all sides, except the south, there are small and scattered rugged hills, which form part of the Aravalli system and extend westwards for some miles; thereafter an unbroken sandy plain stretches away to the west, trees and cultivation becoming more sparse and scanty, and finally it merges into the desert tract of western Rajputana. The station may, therefore, be taken as fairly representative, in point of night temperature conditions, of localities having a sandy soil and situated in about the same latitude in northwest India.

The Meteorological Observatory at Jaipur is at present of class I; it is equipped with self-recording as well as the ordinary eye reading instruments; it was founded in 1875 and is maintained by the State. Before August 1933, when a Stevenson screen was erected for housing the ordinary thermometers, the latter were hung inside a cage under a thatched shed of the standard pattern, formerly used at the observatories of the India Meteorological Department for the exposure of thermometers. The bulbs of the thermometers inside the cage were about 4 ft. above ground. Maximum, dry bulb and wet bulb temperatures, recorded at the observatory at 1600 hrs. local time* and the minimum temperature of the following night, during the period of twelve years, from 1918 to 1929, have been used for the purpose of this investigation. Since low temperatures, which are harmful to crops, occur in this region during clear nights in the cold season, data for those days only on which weather was clear in the night during the above-mentioned period have been considered. As in the previous paper, a night was taken as clear, when the amount of cloud was zero (on the scale 0—10) at 16 hrs. in the preceding afternoon and at 8 hrs. in the following morning.

Monthly frequency of frost.

Frost temperatures at 4 ft. above ground are rare at Jaipur and occur occasionally only in the winter months of January and February. An examination of the temperature data of the station for the period 1880—1929 showed that temperatures of 32°F or less at the height under reference were recorded only five times in January and once in February, the lowest temperature on record at the observatory being 28·1°F on the 31st of January 1905. Owing to radiation from the ground, strong inversions of temperature prevail in clear weather in the surface layers of the atmosphere from evening to early morning; observations made at the observatory show that, during winter, the minimum temperature of the air at 4 ft. above ground may be higher than the grass minimum temperature (bulb ½" above ground) by about 10°F to 12°F on an average[3]. Consequently, in clear weather, when the minimum thermometer at 4 ft. above ground records a temperature of 42°F—a temperature which is generally considered to be the limit below which most of the field and garden crops make little, if any, development,—the simultaneous temperature of the air close to the surface of the ground may be about

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*Local time at Jaipur is behind the Indian Standard Time by about 27 minutes.

32°F. On an average of the period 1918—29, the mean number of days of occurrence of a temperature of 42°F or less, at 4 ft. above ground at the station are 0·1 in November, 3·4 in December, 7·1 in January (the coolest month of the year) and 2·1 in February. Outside these months, such low temperatures have not been recorded at the station.

In the previous paper, the authors had prepared dot diagrams, bringing out the relationship between the *depression* of the dew point below the minimum temperature of the air and

(*a*) dew point of the air, and

(*b*) depression of the dew point below the dry bulb temperature of the air at 1600 hrs. (L. T.).

Since equally good, if not better, estimates of minimum temperature can be obtained from equations derived by the simpler methods of correlation, the dot diagrams have not been prepared in this paper.

Simple Correlations.

Simple correlation coefficients have been worked out between the minimum temperature (N) of the night and the dew point (P), dry bulb (D), wet bulb (W) and maximum (X) temperatures of the air recorded in the preceding afternoon; these are given in *Table 1* together with their respective standard errors.

TABLE 1.

Simple correlation coefficients.

Correlation coefficient (r) between the minimum temperature (N) of the night and the dew point (P), wet bulb (W), dry bulb (D) and maximum (X) temperatures of the air recorded at 1600 hrs. (local time) in the preceding afternoon at Jaipur during the period November—February.

Elements correlated.	November.			December.			January.			February.		
	r	$\pm\frac{1-r^2}{\sqrt{n}}$	n	r	$\pm\frac{1-r^2}{\sqrt{n}}$	n	r	$\pm\frac{1-r^2}{\sqrt{n}}$	n	r	$\pm\frac{1-r^2}{\sqrt{n}}$	n
N and P ..	0·47	0·06	180	0·67	0·05	140	0·52	0·07	105	0·70	0·05	115
N and W ..	0·75	0·03	,,	0·81	0·03	,,	0·65	0·06	,,	0·88	0·02	,,
N and D ..	0·79	0·03	,,	0·61	0·05	,,	0·60	0·06	,,	0·81	0·0[illegible]	,,
N and X ..	0·80	0·03	,,	0·61	0·05	,,	0·61	0·06	,,	0·80	0·03	,,

n = number of observations.

TABLE II.

Regression equations connecting the minimum temperature (N) of the night with the dew point (P), dry bulb (D), wet bulb (W) and maximum (X) temperatures recorded at 1600 hrs. (local time) in the preceding afternoon at Jaipur.

	Regression equation.	Standard error of the estimate $\pm\sigma\sqrt{1-r^2}$
	November.	
1	$N = 0{\cdot}338P + 39{\cdot}0$	4·5°F.
2	$N = 1{\cdot}274W - 24{\cdot}1$	3·4°F.
3	$N = 1{\cdot}040X - 35{\cdot}8$	3·0°F.
4	$N = 1{\cdot}041D - 34{\cdot}1$	3·1°F.
	December.	
5	$N = 0{\cdot}443P + 29{\cdot}7$	4·0°F.
6	$N = 1{\cdot}219W - 22{\cdot}3$	3·2°F.
7	$N = 0{\cdot}668X. - 5{\cdot}1$	4·3°F.
8	$N = 0{\cdot}684D - 5{\cdot}3$	4·3°F.
	January.	
9	$N = 0{\cdot}394P + 32{\cdot}0$	4·6°F.
10	$N = 1{\cdot}208W - 20{\cdot}4$	4·0°F.
11	$N = 0{\cdot}837X - 17{\cdot}8$	4·5°F.
12	$N = 0{\cdot}820D - 15{\cdot}7$	4·6°F.
	February.	
13	$N = 0{\cdot}513P + 34{\cdot}6$	4·7°F.
14	$N = 1{\cdot}409W - 28{\cdot}8$	3·1°F.
15	$N = 0{\cdot}840X - 17{\cdot}1$	3·9°F.
16	$N = 0{\cdot}859D - 18{\cdot}1$	3·8°F.

Table II gives the regression equations between the minimum temperature and each of the other above-mentioned meteorological elements in terms of actual temperatures instead of the departures. The standard errors of the estimates of the minimum temperature from each of the regression equations have also been given; the probable error of an estimate will be about two third of the corresponding standard error.

All the simple correlation coefficients in *Table I* are positive and significant.

The physical relationship between the minimum temperature of the night and the dew point and wet bulb temperatures has already been explained in the previous paper[1] [1931]. A positive correlation between the minimum temperature and the maximum or dry bulb temperature of the air on the preceding afternoon means that, speaking statistically, a warm day is followed by a warm night and a cool day, by a cool night during clear settled weather.

The correlation coefficients of the minimum temperature with the maximum and dry bulb temperatures are almost the same; also the magnitudes of the coefficients and independent terms in the regression equations containing these temperatures as independent variables, either alone as in *Table II*, or in combination with the same second independent variable as in *Table III*, are not very different. This is because the difference between the maximum temperature and the dry bulb temperature at 1600 hrs. (L. T.) at Jaipur on any day is small, the former occurring about an hour earlier, and the difference between them being about 1°F on an average.

Of the various regression equations given in *Table II*, those containing the wet bulb temperature (W) as the independent variable, *viz.*, numbers (2), (6), (10) and (14), generally give the best estimates of minimum temperature, the probable error of the estimate being about 2°F.

Multiple Correlations.

Multiple correlation coefficients were worked out between the minimum temperature (N) and the other meteorological elements under reference, taken two at a time; the values of these coefficients and the corresponding regression equations as well as the standard errors of estimates of minimum temperature (N) are given in *Table III*.

TABLE III.

Multiple correlation coefficients and regression equations.

Multiple correlation coefficient (R) and regression equations between the minimum temperature (N) of the night and the dew point (P), dry bulb (D), wet bulb (W) and maximum (X) temperatures recorded at 1600 hrs. L. T., on the preceding afternoon at Jaipur.

Elements correlated.	R.	n*	Regression equation.	Standard error of the estimate. $\pm\sigma\sqrt{1-R^2}$
			November.	
17 N, W and D	0·85	189	N = 0·661W+0·694D—44·9	2·7°F.
18 N, W and P	0·84	,,	N = 2·424W—0·557P—71·6	2·8°F.
19 N, D and P	0·84	,,	N = 0·944D+0·200P—33·7	2·8°F.
20 N, W and X	0·85	,,	N = 0·647W+0·708X—46·4	2·7°F.
21 N, X and P	0·85	,,	N = 0·946X+0·201P—35·5	2·7°F.
			December.	
22 N, W and D	0·81	140	N = 1·254W—0·0349·D—21·7	3·2°F.
23 N, W and P	0·81	,,	N = 1·161W+0·0308·P—20·2	3·2°F.
24 N, D and P	0·81	,,	N = 0·514D+0·361P—5·8	3·2°F.
25 N, W and X	0·81	,,	N = 1·224W—0·00551X—22·2	3·2°F.
26 N, X and P	0·81	,,	N = 0·509X+0·365P—6·3	3·2°F.
			January.	
27 N, W and D	0·66	105	N = 1·182W+0·0790D—22·1	4·0°F.
28 N, W and P	0·65	,,	N = 1·420W—0·0963P—28·7	4·0°F.
29 N, D and P	0·68	,,	N = 0·575D+0·274P—6·2	4·1°F.
30 N, W and X	0·67	,,	N = 1·047W+0·161X—23·7	4·0°F.
31 N, X and P	0·68	,,	N = 0·601X+0·260P—8·3	4·1°F.
			February.	
32 N, W and D	0·88	115	N = 1·317W+0·0675D—29·0	3·0°F.
33 N, W and P	0·88	,,	N = 1·544W—0·0750P—34·1	3·1°F.
34 N, D and P	0·87	,,	N = 0·651D+0·281P—9·8	3·2°F.
35 N, W and X	0·88	,,	N = 1·297W+0·0817X—29·1	3·1°F.
36 N, X and P	0·87	,,	N = 0·633X+0·285P—9·0	3·2°F.

* n= number of observations.

The significance of each of the multiple correlation coefficients was tested by analysing the variance into its two components, (*a*) that due to the regression formula and (*b*) that due to deviations from the regression functions and determining by means of the 'Z' test of Fisher[4] [1925] whether the mean values of the two were significantly different. All the coefficients were found to be significant.

The standard error of the estimate of minimum temperature (N) from the various regression equations in *Table III* is about the same, *viz.*, about 3°F, except during January, when it is about 4°F. Since dry bulb, wet bulb and maximum temperatures are directly observed on the preceding afternoon and dew point has to be calculated from the observed values of dry bulb and wet bulb temperatures, the most convenient equations to use for calculating the minimum temperature of the night are those which contain either (1) dry bulb and wet bulb or (2) maximum and wet bulb temperatures as independent variables; the observed and calculated values agree fairly closely. The percentage frequencies of occurrence of the various values of differences between the observed and the calculated values of minimum temperature from equations containing the dry bulb and wet bulb temperatures as independent variables are given in *Table IV*.

TABLE IV.

Percentage frequencies of occurrence of the various values of differences in °F between the observed and calculated values of minimum temperature.

Month.	Difference in °F.											Percentage of cases in which the diff. was 5°F. or less.	Total No. of obsns.
	O.	±1	±2	± 3	± 4	± 5	±6	±7	±8	±9	±10		
	%	%	%	%	%	%	%	%	%	%	%	%	
November ..	16·4	25·4	25·4	15·3	9·0	5·8	0·0	1·6	1·1	..	..	97·3	189
December ..	16·4	25·0	21·4	16·4	5·7	7·9	3·7	1·4	0·7	0·7	0·7	92·8	140
January ..	8·3	21·7	20·8	15·0	16·7	10·8	0·8	1·7	1·7	0·8	1·7	93·3	105
February ..	17·4	25·2	19·1	14·8	9·6	6·1	3·5	3·5	..	0·8	..	92·2	115
All months (November—February).	14·9	24·6	22·2	15·4	9·9	7·4	1·8	1·9	0·9	0·5	0·5	94·4	549

Table IV shows that:—

(*a*) the most frequent difference between the observed and calculated values of minimum temperature is about 1°F to 2°F; and that,

(*b*) the observed and calculated values of minimum temperature agree within ±5°F in about 97% cases in November, 93% cases in December and January, 92% cases in February, and, on an average, in over 94% cases in the period November to February. The discrepancies in the remaining 6% of the cases are not large, and an examination of the daily weather charts indicates that these were generally associated with the western disturbances moving across the station.

It has been tacitly assumed in the foregoing discussion that there is no change in the physical properties of the air at the station between the time of observation and the epoch of the minimum temperature. If, however, a change occurs, *i.e.*, if the air mass at the station in the afternoon is replaced by the following morning either by (1) a warmer and more humid or (2) colder and drier air, large discrepancies in the observed and calculated values of minimum temperature are to be expected, since the observed values of dew point, wet bulb, dry bulb and maximum temperatures will no longer be applicable to the air mass in which the minimum temperature of the night occurs. Over the region under consideration, such changes in the air mass in winter are mostly associated with western disturbances or depressions, which affect the station at intervals and more frequently in January than in the remaining three months.

The physical significance of the equations, expressing minimum temperature in terms of the independent variables contained in the regression equations in *Tables II* and *III* has already been commented upon generally by the authors in the previous paper.

Minimum Temperature and the Pressure Distribution.

One of the most important features of the pressure distribution over northern India in the cool season is the western distrubances or depressions, which travel eastwards or eastnortheastwards across northern India at the average rate of 300—400 miles per day. These disturbances are often occluded and are ill-defined on the synoptic weather charts. When well marked, they generally show sharp warm and cold fronts like depressions of the temperate latitudes. When Jaipur lies in the warm sector of a disturbance, the air is warm and moist. The wind is from an easterly to some southerly or southwesterly direction and the skies are often cloudy. Frost does not occur under these conditions. With the passage of the cold front, the easterly to southerly winds are replaced by westerly to northwesterly winds, which are usually much stronger, colder and drier than the normal northwesterly or northnorthwesterly winds of the season. These unusually cold and dry winds blow in the rear of the disturbance for about a couple of days, when the skies are also clear. Under the combined effect of these cold winds and strong radiation from the ground at night, the minimum temperature may fall down to the freezing point.

Frost may also occur during unusually long spells of dry and clear (anti-cyclonic) weather as a result of the cumulative effect of radiation from the ground on successive nights.

Conclusions.

From the foregoing discussion it would appear that frost temperatures occur at Jaipur in winter in the cold wave in the rear of a western disturbance or during unusually long spells of clear and dry (anti-cyclonic) weather. Within about ±3°C, the minimum temperature of the air on a clear night at Jaipur can be forecasted from the wet bulb and dry bulb or maximum temperatures of the preceding afternoon with an accuracy of over 94 per cent. The best equations to be used for the purpose are those containing either,

(1) wet bulb and dry bulb temperatures, or

(2) wet bulb and maximum temperatures as independent variables, *vide Table III.*

Equations containing wet bulb temperature alone as independent variable (*vide Table II*) generally give results that are equally good and have the further advantage of containing only one independent variable; these equations are useful as checks on the values obtained from the above mentioned equations with two independent variables. The discrepancies observed in the remaining 6% of cases, are generally not large, and these mostly arise owing to the changes brought about by rapidly moving western disturbances in the physical properties of the air at the station during the interval between the afternoon observations and the epoch of minimum temperature. On such occasions, the afternoon temperature observations are not characteristic of the air, in which the minimum temperature of the night occurs. A forecaster provided with the facilities of a synoptic weather chart can, however, in most cases, foresee these changes and make a due allowance for these occasions.

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HEAT RADIATION FROM THE ATMOSPHERE AT BOMBAY AND ITS COMPARISON WITH THAT AT POONA.

BY

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(Received on 5th July 1940.)

Abstract.—In India, systematic observations of atmospheric radiation had been made only at Poona With a view to extend our knowledge, daily measurements of the net loss of heat by radiation from a black surface exposed to the sky were made at Bombay during the period March 1937 to October 1938 with an Ångström's pyrgeometer. Simultaneous observations of temperature, vapour pressure and cloudiness were also recorded. From the net radiation, the radiation received from the atmosphere is calculated and its variations with season, cloudiness and state of weather are discussed. The results are compared with those obtained at Poona. Net radiation from a horizontal surface and the depression of the grass minimum temperature below that of the Stevenson screen minimum are correlated. A brief discussion is made of the conditions under which abnormally low or high values of sky radiation are observed.

Introduction.

In recent years, considerable attention has been directed to the study of the heat radiation from the atmosphere. The experimental work of Ångström[1] and the theoretical calculations of Simpson[2] have shown clearly that atmospheric water-vapour is responsible for practically all the radiation from the atmosphere and that in clear weather, the amount of sky radiation received at the surface of the ground may be expected to lie between 0·50 to 0·80 of the radiation from a black body at the temperature of the air near the ground—the former value corresponding to extremely dry conditions of the atmosphere and the latter to extremely moist conditions.

The study of the heat radiation emitted by the atmosphere in many parts of the world has shown that during clear weather, the downward radiation from the night sky expressed as a fraction of the black body radiation at the temperature of the air near the instrument decreases on the mean with increase of vapour pressure as measured near the ground in approximate agreement with Ångström's equation

$$S/\sigma T^4 = A - B.10^{-\gamma e}.$$

where S is the heat radiation incident per square centimetre of a horizontal surface in gramme calories per minute, T is the temperature in degrees absolute and e the aqueous vapour pressure of the air near the pyrgeometer, σT^4 is the black body radiation at temperature T °A, and A, B and γ are constants.

In 1937 regular measurements of atmospheric radiation were commenced at the Colaba Observatory, Bombay, with a two-fold object (1) to obtain systematic values of atmospheric radiation under conditions of high humidity such as generally obtained at tropical coastal stations and (2) to compare the night radiation at an interior station (like Poona in the Bombay Deccan) with that at a coastal station (Bombay). The measurements made at Colaba during the period March 1937 to September 1938 are discussed in the present paper. The results obtained are compared with those obtained at Poona in 1930-31.

Comparison of the climates of Bombay and Poona.—While the climate of Bombay is maritime in character, that of Poona, during the major part of the year, is of the continental type.

As is to be expected from their respective locations, Bombay is more humid than Poona throughout the year. In both the places, rainy weather is almost entirely confined to the monsoon season from June to September ; the rest of the year (except for May and October, when thunderstorms occur occasionally), is mainly clear and dry. The rainfall at Bombay is 70″ per year, but Poona, on the lee-ward side of the Ghats, gets only 27″. During the monsoon season, both at Poona and Bombay, the south-westerly wind is strong, being more than 10 m.p.h. on an average. During the rest of the year, however, the wind is weak at Poona, but a moderate air movement continues at Bombay, especially in the afternoon hours, owing to sea-breeze. Thus, during more than half the year, while Poona has a continental climate with light winds, a large diurnal variation of temperature and moderate to low humidity. Bombay continues to be humid and breezy with moderate temperatures. The weather at both the places is generally clear throughout the dry season, as this part of India is more or less outside the influence of the north-east monsoon and of the western disturbances.

Calibration of the Ångström's pyrgeometer used at Bombay.—The instrument that was used for measuring nocturnal heat radiation at Bombay was an Ångström's pyrgeometer made by Mr. G. Rose of Upsala (No. 48). This is the same instrument as that used by Ramanathan and Desai[3] for their observations at Poona in 1930-31.

An Assmann's psychrometer was used to record dry and wet bulb temperatures. From these, e the vapour pressure was calculated ; the temperature T was the same as that of the dry bulb near the instrument.

The instrumental constant K of the pyrgeometer was obtained either by comparison with a standard instrument or by calibrating it by exposing it to full black body radiation from a suitable radiator kept at different temperatures.

As the constant might have changed with time, it was re-determined in the laboratory by exposing it to the radiation from a hollow black cavity forming part of a metal vessel. The radiating surface of the cavity could be kept at different temperatures by filling the vessel with well-stirred water at the required temperatures. The compensating current which had to be passed through the black strip in order to equalise the temperatures of the black and bright strips of the pyrgeometer was measured. Another radiating source used for calibration was a hemispherical cavity in a big block of ice about 2 ft. × 2 ft. × 1¼ ft. The cavity was kept free from melted water and gentle fanning was used to prevent stagnation of air. Some results of the measurements are shown in *Table 1.*

TABLE I.

Calibration of pyrgeometer No. 48.

T_1 = Temperature of air near the pyrgeometer.

T_0 = Temperature of radiating surface.

i = Current in amperes required to equalise the temperatures of the strips.

K = Constant of instrument in the equation.

$$\text{Net Radiation} = Ki^2$$

Experiments with radiating source in the laboratory on 7th October 1937.

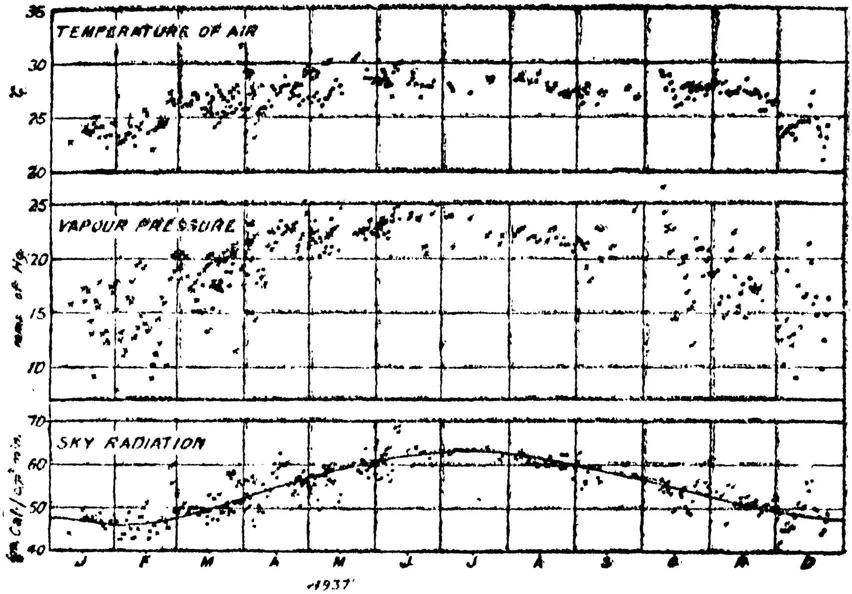
1	2	3	4	5	6
T_1 °C.	T_0 °C.	$(T_1^4 - T_0^4)$	i (Amperes)	Ki^2	Remarks.
27·0	0·8	0·204	0·138	0·204	Radiator was a cavity on the side of a metal vessel filled with water.
23·5	4·4	0·185	0·131	0·184	
24·4	11·2	0·106	0·100	0·107	
26·7	15·0	0·097	0·095	0·097	
27·0	18·2	0·075	0·081	0·071	
27·6	23·0	0·040	0·060	0·039	
26·0	0	0·200	0·135	0·196	Radiator was a cavity in a big block of ice.
25·6	0	0·196	0·132	0·187	
25·0	0	0·191	0·132	0·187	

The values Ki^2 in column 5 were calculated assuming the value of K to be 10·75.

The agreement of the figures in columns (3) and (5) shows that the assumed value of the constant can be considered satisfactory.

Net radiation, sky radiation, and related meteorological elements at Bombay.

The net radiation being the difference between the sky radiation and the black-body radiation at the temperature of the instrument depends on the temperature of the air near the instrument; on cold nights, its value will depend very much on whether the observations are made very near the ground or at the top of a tower. The sky radiation S, although to some extent dependent on T is less affected by the variations of temperature near the ground.



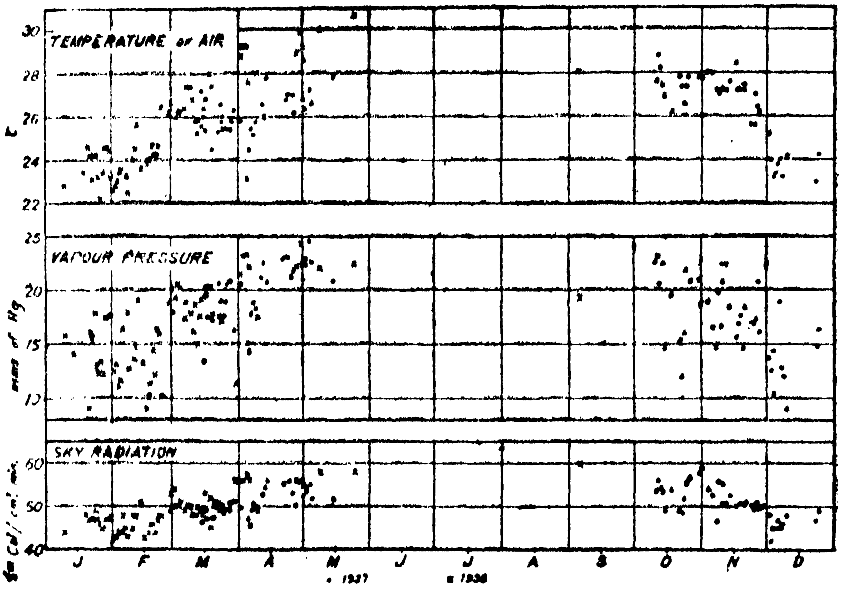
DAILY VALUES OF SKY RADIATION, TEMPERATURE and VAPOUR PRESSURE at BOMBAY 1937-38, (ALL DAYS).

Fig. 1.

In *Fig. 1* are plotted the daily values of T, *e* and S at Bombay against the day of the year. In this figure, the values for all days, both clear and cloudy, have been included. Although there is a certain amount of scatter in the points and the number of observations in the months June to September is comparatively small, the similarity in the seasonal march of variation of T, *e* and S and particularly of *e* and S are brought out clearly by the curves. The low values of T and *e* in winter are associated with comparatively small values of S. All the elements increase in value in March, April and May. Both the vapour pressure and sky radiation attain maximum values in June and July. The temperature curve shows a drop at the beginning of June corresponding to the onset of the monsoon, but the increase of moisture in the atmosphere and cloudiness makes up for the fall in temperature—so that the values of S continue to be high in June, July and part of August. The lowest observed value of sky radiation at Bombay is 0·41 gm. cal/cm^2. min., and the highest 0·66 gm. cal/cm^2. min., the lowest and highest values of $S/\sigma T^4$ being 0·64 and 0·96. The lowest values of $S/\sigma T^4$ occur on days of very clear weather with dry northerly winds in winter or early hot season and the highest values on overcast days during the monsoon.

No observations were made on days when it was actually raining during 21-23 hrs. or on days when the cloud amount was varying so rapidly that no definite determination could be made.

Clear days only.—Excluding cloudy days and considering clear days only, the annual variation of S is very similar in character. The number of observations, however, is considerably diminished, particularly in the monsoon period. (Fig. 2).



DAILY VALUES OF SKY RADIATION, TEMPERATURE AND VAPOUR PRESSURE AT BOMBAY, 1937-38. (CLEAR DAY).

Fig. 2.

Monthly mean values of net radiation and sky radiation at Bombay and Poona.

The monthly mean values of sky radiation, net radiation and $S/\sigma T^4$ together with the corresponding values of temperature and humidity are given in *Table II* and represented graphically in *Fig. 3*. For comparison, the monthly mean values of the same quantities for Poona, taken from the paper by Ramanathan and Desai are also given. The numbers of observations in each month at the two places are not very different, so that a comparison of the values at the two places is justifiable. The observations at both the places were also made from the tops of towers, so that the temperatures are not affected by the large ground inversions which are common in winter. In both the places, the radiation from the sky is a maximum in the monsoon months and a minimum in winter. In all the months except October, the mean sky radiation observed at Bombay is greater than that observed at Poona, which is to be expected, considering the higher values of surface humidity prevailing there. A comparatively large value of sky radiation is observed at Poona in October and this is perhaps due to the fact that in this month, the flow of upper air over Poona is often from an easterly direction and although the surface air at Bombay is more moist, it is possible that as a whole, the air over Poona contains more moisture than that over Bombay. The years also are different.

The monthly mean values of radiation and other related quantities on clear days alone are given in *Table III.*

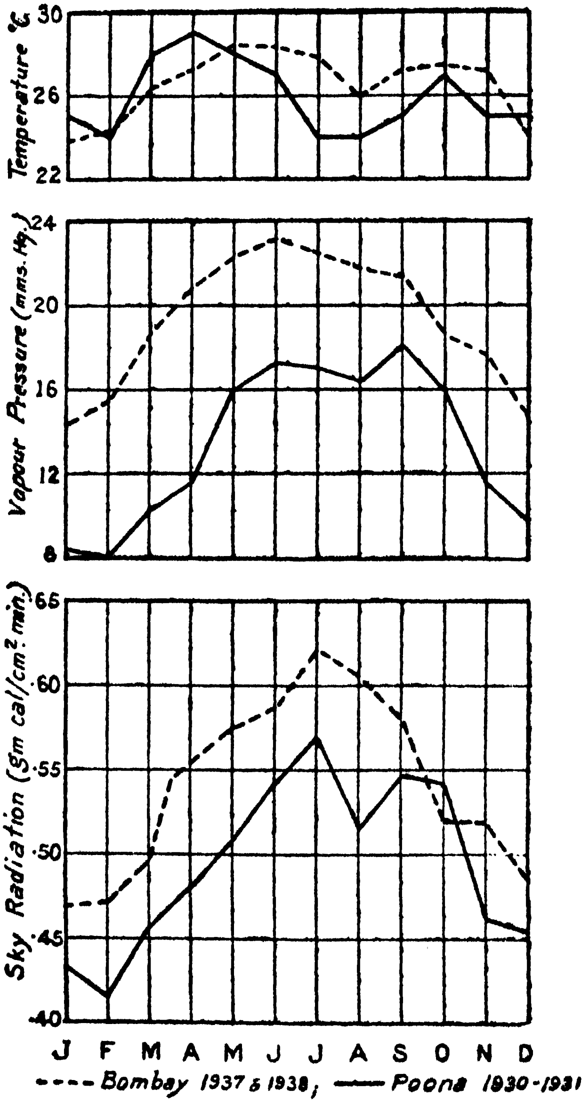


Fig. 3.

TABLE II.

Mean monthly values of night radiation at Bombay (all days).

(For comparison, the values for Poona taken from Ramanathan and Desai's paper are also included).

Month.	Place.	No. of observations. n	Air temp. °C	Vap. pressure. mm. Hg.	Net radiation R. gm. cal. / cm². min.	Sky radiation S. gm. cal. / cm². min.	$\frac{S}{\sigma T^4}$.
January ..	Bombay ..	17	24	14·3	0·178	0·468	0·74
	Poona ..	31	25	8·5	·201	·433	·68
February ..	Bombay ..	26	24	15·4	·175	·471	·76
	Poona ..	34	24	8·1	·215	·416	·66
March ..	Bombay ..	45	26	18·7	·170	·495	·75
	Poona ..	29	28	10·3	·214	·456	·68
April ..	Bombay ..	40	27	20·9	·119	·541	·82
	Poona ..	27	29	11·6	·194	·481	·71
May ..	Bombay ..	33	28·5	22·2	·103	·573	·85
	Poona ..	25	28	16·0	·161	·508	·76
June	Bombay ..	24	28	23·1	·061	·586	·87
	Poona ..	20	27	17·3	·114	·541	·83
July ..	Bombay ..	7	28	22·5	·050	·621	·93
	Poona ..	8	24	17·1	·064	·569	·90
August ..	Bombay ..	17	26	21·8	·064	·606	·89
	Poona ..	17	24	16·4	·115	·514	·82
September ..	Bombay ..	12	27	21·4	·078	·580	·88
	Poona ..	8	25	18·1	·097	·542	·85
October ..	Bombay ..	22	28	18·6	·122	·522	·82
	Poona ..	17	27	15·9	·117	·542	·82
November ..	Bombay ..	25	27	17·7	·143	·521	·79
	Poona ..	26	25	11·6	·176	·462	·72
December ..	Bombay ..	22	24	14·7	·154	·484	·76
	Poona ..	28	25	9·9	·184	·455	·71

TABLE III.

Mean monthly values of night radiation at Bombay (clear days).

(For comparison the values for Poona taken from Ramanathan and Desai's paper are also included)

Month.	Place.	No. of observations. n	Air temp. °C	Vap. pressure. mm. Hg.	Net radiation R. $\frac{\text{gm. cal.}}{\text{cm}^2\text{. min.}}$	Sky radiation S. $\frac{\text{gm. cal.}}{\text{cm}^2\text{. min.}}$	$\frac{S}{\sigma T^4}$.
January ..	Bombay ..	14	24	14·2	0·170	0·463	0·727
	Poona ..	30	24	8·5	·207	·430	·675
February ..	Bombay ..	22	24	14·2	·180	·460	·722
	Poona ..	34	24	8·1	·215	·416	·653
March ..	Bombay ..	30	26	18·1	·159	·498	·761
	Poona ..	25	27	9·9	·225	·444	·671
April ..	Bombay ..	22	27	19·7	·133	·525	·794
	Poona ..	20	28	11·0	·214	·498	·742
May ..	Bombay ..	7	28	22·5	·126	·547	·815
	Poona ..	16	28	16·5	·171	·493	·735
June ..	Bombay ..	..	..	..	..	..	..
	Poona ..	6	27	16·7	·173	·488	·737
July ..	Bombay ..	..	..	..	..	..	..
	Poona ..	..	..	..	..	..	..
August ..	Bombay ..	..	..	..	..	..	..
	Poona ..	..	..	..	..	..	..
September ..	Bombay ..	1	28	19·3	·112	·559	·833
	Poona ..	2	25	17·9	·149	·495	·769
October ..	Bombay ..	13	27	19·1	·144	·534	·807
	Poona ..	18	28	12·7	·176	·502	·748
November ..	Bombay ..	18	27	17·3	·150	·520	·785
	Poona ..	22	24	10·3	·191	·445	·699
December ..	Bombay ..	10	24	13·5	·173	·474	·744
	Poona ..	23	25	8·8	·244	·422	·654

Net radiation from an exposed horizontal surface and the depression of the grass minimum temperature below that of the minimum in the Stevenson screen (4 ft. above ground).

It is well-known that the minimum temperature recorded by a thermometer exposed a couple of inches above ground is generally lower on a clear night than the minimum temperature in a normal Stevenson screen. This is mainly due to the cooling of the ground by radiation and the spreading of this low temperature upward by eddy diffusion. The direct cooling of the air itself by radiation and the collection of the cooled air near the ground also plays a part. In the neighbourhood of hills and in valleys, the downward drain of cooled air from the hill slopes and their collection in the valleys is also important. The phenomenon is thus complicated, and in general, the difference between the grass minimum and the screen minimum temperatures is affected by local factors in addition to the loss of heat by radiation during the night. Still, it will be useful to collect together the data regarding net radiation and excess cooling of the grass minimum thermometer below the Stevenson screen minimum and compare the results at Bombay and Poona.

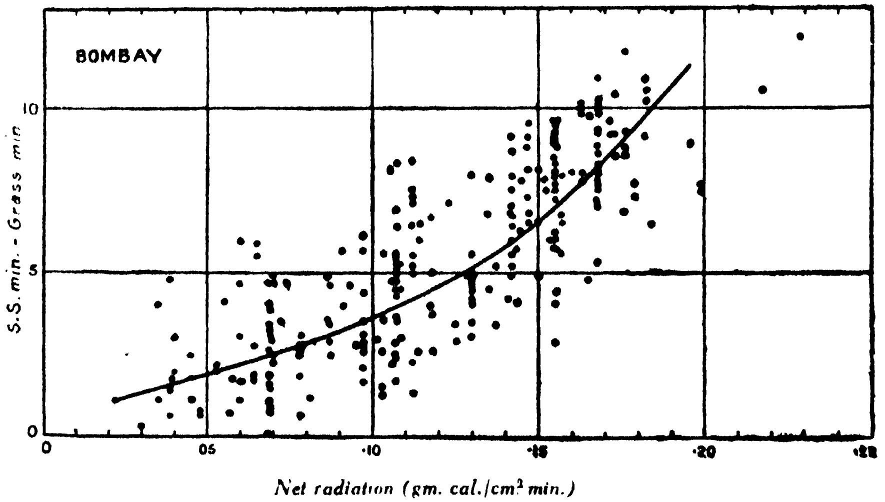


Fig. 4.

In Fig. 4 are plotted the daily values of the quantity (Screen minimum temperatures minus grass minimum temperatures) against the net radiation at Bombay. It is evident from the figure that the temperature stratification near the ground increases in intensity as the net radiation increases and the rate of increase of the intensity of stratification increases at the higher values of net radiation. Comparing with similar data at Poona in Ramanathan and Desai's paper[3] the rate of increase of stratification with increase of net radiation is greater at Bombay than at Poona. *Table IV* which compares the monthly mean differences between these two temperatures at Bombay and Poona shows that it is during the cold season months November to February that these excess differences at Bombay mainly occur. This is probably due to the fact that owing to the greater relative humidity of the air at Bombay, the bulb of the grass minimum thermometer there gets on many days in winter a deposit of condensed water and acts as a wet bulb instead of as a dry bulb.

TABLE IV.

Monthly mean differences of Stevenson screen minimum and grass minimum temperatures at Bombay and Poona.

Month.	S.S. Minimum—Grass minimum.		Remarks.
	Bombay.	Poona.	
January	7·7	5·9	The differences at Bombay are greater in the cold season November to February.
February	9·5	6·4	
March	7·1	7·5	
April	5·5	6·5	
May	3·7	6·3	
June	1·6	3·0	
July	0·9	1·7	
August	1·5	3·5	
September	1·7	3·0	
October	4·4	3·7	
November	7·6	4·7	
December	8·2	5·0	

Arranging the differences screen minimum minus grass minimum according to the values of net radiation, we get the following table for Bombay.

TABLE V.

Grouped means of Stevenson screen minimum minus grass minimum temperatures corresponding to different values of net radiation on the previous night.

Net radiation (gm. cal./cm.^{2} min.).	No. of observations.	Mean of (S.S. min.—Grass min.).
0·02—·04	9	2·0
·04—·06	13	1·9
·06—·08	38	3·0
·08—·10	21	3·4
·10—·12	48	4·7
·12—·14	21	4·9
·14—·16	59	7·1
·16—·18	48	8·4
·18—·20	18	9·9
·20—·22	4	11·5

Variation of radiation during the course of the night.

Raman[4] has discussed the nocturnal variation of radiation S on clear nights from hourly observations recorded at Poona and its neighbourhood. *Table VI* gives a typical example of the data recorded at ground level at the Agricultural College Observatory, Poona. It will be noticed that although the variation in the vapour pressure is small, there is a large variation in the value of T and S. Apart from an actual change in the properties of the air mass pervading the upper atmosphere, the cooling of the air layers near the ground is responsible for the variation in S, the decrease being mainly in the S_3 (high absorption) region of the heat radiation.

If one takes observations above a level at which the variations during the night are small, one would not expect any significant variation of the sky radiation during the night. In *Table VII* are given the hourly observations recorded at Bombay on the nights of 26th March 1937, 18th January 1938, and 2nd February 1938 which were all clear. The values of S on these dates do not show any significant variations during the course of the night. On examining the values of T, one notes that the variation of T also was very small, being less than 2°C.

TABLE VI.

Diurnal variation of sky radiation at Poona.

(*From P. K. Raman, Proc. Ind. Acad. Sci., 1936*).

Date.	Time I. S. T.	Temperature °C.	Vap. pressure mm. Hg.	Net radiation.	Sky radiation.	Remarks.
9th March 1935 ..	2000	27·3	1·9	0·226	0·439	Very clear sky.
	2200	24·0	2·8	·234	·403	Do.
	2400	23·0	3·3	·214	·414	Do.
10th March 1935 ..	0200	21·2	3·1	·205	·406	Do.
	0400	19·0	2·5	·205	·390	Do.
	0600	17·5	3·3	·190	·393	Do.

TABLE VII.

Diurnal variation of sky radiation at Bombay.

Date.	Time I. S. T.	Temperature °C.	Vap pressure mm. Hg.	Net radiation.	Sky radiation	Remarks.
26th March 1937 ..	1930	26·4	19·4	·168	0·489	Very clear sky.
	2000	25·2	19·6	·155	·492	Do.
	2200	25·5	19·8	·155	·494	Do.
	2400	25·4	20·6	·155	·494	Do.
27th March 1937 ..	0200	24·4	19·3	·142	·498	Do.
	0330	24·6	20·3	·157	·485	Do.
	0430	24·6	19·9	·155	·487	Do.
	0630	25·8	20·7	·157	·495	Do.
18th January 1938 ..	1900	24·4	15·0	·168	·472	Very clear but Hazy.
	2000	24·2	15·4	·163	·475	Do.
	2200	23·4	14·0	·155	·476	Do.
	2400	23·2	14·3	·155	·476	Do.
	0200	23·2	12·3	·163	·475	Do.
	0400	22·6	13·9	·155	·469	Do.
	0500	22·7	12·3	·168	·457	Do.
2nd February 1938 ..	2000	23·4	13·1	·208	·423	Very clear.
	2200	22·8	13·1	·199	·427	Do.
	2400	22·3	12·7	·196	·426	Do.
	0200	21·6	13·1	·196	·420	Do.
	0400	20·6	12·7	·190	·418	Do.
	0600	21·6	8·2	·194	·432	Do.

Occasions of abnormal values of sky radiation.

It is of interest to examine under what circumstances exceptionally large deviations in the values of the sky radiation from the values calculated according to Ångström's formula occur.

We can divide the observations at Bombay into three classes :—

(1) days on which the agreement with Ångström's formula can be considered good,

(2) days on which the observed values are much below the calculated values

and (3) days on which the observed values are much above the calculated values.

Selected days on which the observed values are much below the calculated values.

Date.	T.	*e*.	$S/\sigma T^4$.	Remarks.
17th March 1937	24·2	15·4	0·641	Very clear sky.
18th March 1937	25·4	17·3	·693	Do.
2nd December 1937	24·0	12·5	·659	Very clear sky; dry cold wind.
31st January 1938	23·2	7·9	·665	Very clear sky and strong westerly wind.
8th February 1938	22·4	12·7	·685	Very clear; strong breeze.
9th February 1938	24·2	19·4	·678	Very clear; strong breeze.

On these and similar days when $S./\sigma T^4$ was abnormally low, the skies were very clear and there were winds of northerly origin in the first 3 km. in the atmosphere over Bombay.

Abnormally high values of $S./\sigma T^4$.

Date.	T.	*e*.	$S/\sigma T^4$.	Remarks.
5th July 1937	27·4	21·0	0·941	Clear sky.
1st September 1937	27·2	21·9	0·920	Clear sky.
1st November 1937	28·4	18·4	0·890	Clear; but hazy.
8th November 1937	27·0	19·8	0·839	Clear sky; hazy.
9th November 1937	27·2	16·6	0·832	Clear sky; hazy.
1st April 1938	28·8	21·5	0·832	Clear sky. Fine weather with Ac and Cu till evening; distant lightning between 20 and 20-45 hrs.
2nd April 1938	29·2	23·2	0·827	Clear sky. Fine weather with Cu, Sc and Cb and thunder between 17 and 18-45 hrs.
4th April 1938	29·2	23·2	0·833	Very clear sky.
5th April 1938	27·6	22·1	0·840	Very clear sky; SE wind.
26th April 1938	28·0	20·0	0·855	Very clear sky.
28th April 1938	29·4	25·1	0·858	Very clear sky; breezy.
8th May 1938	30·0	22·0	0·845	Clear sky. Light Sc and St.
24th May 1938	30·6	22·5	0·839	Clear sky; no breeze. Light to moderate clouds.
27th July 1938	28·2	21·4	0·911	Very clear sky; breezy.
5th September 1938	28·0	19·3	0·833	Very clear sky; slight breeze.
23rd September 1938	27·5	21·0	0·904	Very clear sky; calm.
27th September 1938	26·8	24·4	0·882	Very clear sky; breezy.

In the months April to September, and even on some occasions in November, days occur when the atmosphere is cloudless, but the value of $S/\sigma T^4$ is greater than 0·83. The reason for this is not clear. One obvious reason which suggests itself is that there might have been a mistake in judging the clearness of the sky at night and that it might have been really partly clouded. But this is not probable except on very few occasions.

During monsoon, on rare occasions, it happens that the reading of the galvanometer indicates a net gain of heat by radiation. This happened on two occasions during the present period of observation, once on 13th July 1937 and another time on 18th June 1938. In a condition like this, the cloud apparently radiates as a body at higher temperature than the element of the pyrgeometer.

In conclusion I wish to express my thanks to Dr. K. R. Ramanathan under whose guidance the above work was carried out. Also I wish to acknowledge with thanks the help rendered by Mr. P. K. Raman in calibrating the Ångström's pyrgeometer.

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Photographic studies of some cloud forms and their changes with time.

BY

M. W. CHIPLONKAR.

(Received on 26th October 1940.).

Abstract.—In recent years, many laboratory studies have been carried out on the motion generated in shallow unstable layers of fluids producing artificial cloud patterns which greatly resemble the strato-cumulus, alto-cumulus and cirro-cumulus clouds and also those of the böen type. During the last two years, the author has attempted to obtain systematically photographs of some types of natural clouds at short intervals of time in order to study the changes which they undergo. In this paper are reproduced and discussed some of these series of cloud photographs taken at Poona.

Introduction.

The movement and appearance of clouds give us valuable information about the physical conditions of the atmospheric layers in which they are embedded. In recent years, many laboratory studies have been carried out of the motion generated in layers of fluid caused by heating from below or by the movement of a mass of denser fluid within a lighter one and have yielded a good deal of insight into the processes of formation of certain kinds of clouds. Of these, the studies of Benard, Idrac, Walker, Mal, Graham, Krishna Chandra and others on instability clouds[1] of the strato-cumulus, alto-cumulus, and cirro-cumulus types, and of Schmidt and Ghatage on cloud forms of the böen type[2] are the most noteworthy.

During the last two years, the writer has attempted to obtain systematically photographs of some types of clouds at short intervals of time in order to make a study of the changes which they undergo.

In this note some of these cloud photographs are re-produced and briefly discussed.

Experimental.

The photographs of the clouds were taken at regular intervals with a " Pilot " miniature camera having a maximum aperture of f/2·7 and focal length 5 cm. Panchromatic films with a red filter R G 1 of Schott and Genossen were used. The interval between successive photographs was generally 30 seconds.

In the following illustrations, only a few of these pictures have been selected and the interval between consecutive pictures was 1 to 2 minutes. All the photographs reproduced were taken at Poona.

Rising cumulus.—(Plate I).

(*Date 11th May 1940. Time 1645/1m/1650 hrs.*).

This series of pictures was taken in the afternoon commencing at 16 h. 45 m. I. S. T. The camera was facing the south. The six photographs reproduced show successive stages of development of a rapidly growing cumulus at intervals of one minute each. The two heads (clearly seen in the last two pictures) reared themselves with great rapidity. The upper winds observed at 14 hrs. on the afternoon of the day were from the east between 2·1 and 3·4 km.

Large cumulus, later spreading into Strato-cumulus.—(Plate II).

(*Date 21st September 1939. Time 1615/1m/1618; 1655; 1656; 1800; 1825 hrs.*).

The first four pictures were taken at intervals of one minute each. The formation of " anvils " at the top of the cumulus cloud can be clearly seen in them. The rapid growth of the massive head on the right of the last picture may be noted. A very rough estimate of the rates of ascent of the cumulus heads in *Plates I* and *II* shows that they were of the order of 20 km/hr. Pictures (*e*) and (*f*) taken 37 and 38 minutes later (at 1655 and 1656 hrs.) facing north show that the cloud tops had reached the inversion layer and begun to evaporate. They had also moved towards the camera. Photographs (*g*) and (*h*) taken at 1800 hrs. and 1825 hrs. respectively show the spreading out of the cumulo-nimbus cloud into a huge stratus covering half the sky. In the last two stages, mammato-structure was developed; the rolling structure of the under-surface of the cloud is discernible in the last picture.

Transverse rolls in a stratiform cloud.—(Plate III).

(*Date 5th March 1940. Time 0841/1m/0845 hrs.*).

The upper winds as shown by the morning pilot balloon ascent were from NW up to 1·4 km. and WSW to W above upto 6 km. The wind speed increased rapidly above 2·1 km. and the cloud probably formed at a height of about 2 km. In the afternoon also, the winds were from the west up to 6·9 km.

The irregularity of the waves and the rib-like structure at right angles to the rolls may be noted. The first photograph (*a*) shows a doubling of three of the rolls on the right hand top corner. These are marked on the margin. As explained by Graham[3] and Walker[1], the doubling is due to the existence of two vortices with opposite rotations in each main roll. The exposures were taken facing the west and the waves were moving rapidly towards the zenith. The last picture was taken when the cloud was nearly overhead.

Transverse and longitudinal rolls in the same sheet of cloud.—(Plate IV).

(*Date 5th April 1940. Time 1230/30 s/1232 hrs.*).

The doubling of the transverse rolls (marked in picture (*e*)) is more clearly shown in the next series of photographs, obtained on 5th April 1940 at about noon. The upper winds observed at 14 hrs. of the day were weak southerly up to 4 km. and stronger westerly to south-westerly above. The clouds were probably formed at a height of about 4 km. where there was a change in direction and also increase in speed. The photographs, especially the first and second, also show longitudinal rolls in the same sheet of cloud. The latter show considerable staggering similar to what Krishna Chandra[4] observed with smoke columns in the laboratory when there was a shearing movement in the air contained in a 6 mm. chamber. As the shear gets smaller, the longitudinal structures become shorter, and more irregular. Ribs often seen in transverse rolls are apparently of the same character, being the elements out of which the "spirals" of the longitudinal rolls are built up.

Transverse rolls and cells.—(Plate V).

(Date 19th July 1939. Time 0750/2m/0756 hrs.).

The formation of transverse rolls in a stratified layer, and development of irregular polygonal cells tending to form a cross-pattern are shown in these photographs. The softness of outline in photographs (*a*) and (*b*) is in marked contrast to the turbulence manifested in photograph (*d*). The last photograph also shows the doubling of some of the transverse rolls. These photographs remind one of the instability pictures of Krishna Chandra[4] in which the depth of the chamber varied from 6mm. to 8 mm.

The last picture in the plate belongs to a different series (30th March 1939, 1849 hrs.) and shows how the rapid spreading of the top of a cumulo-nimbus cloud into an anvil often causes longitudinal rolls to appear.

Sheet cloud broken up into polygonal flower-like cells.—(Plate VI).

(Date 10th April 1939. Time 1120/1m/1123 hrs.)

The photographs (*a*) to (*d*) were taken with the camera facing the zenith. The internal movements in this type of cloud are generally too slow to be noted with the naked eye. The successive pictures do not show any wholesale changes in pattern, but the intensification or weakening of some of the lines or foci of descent can be clearly seen. It will be noticed that the comparatively larger cells have faint spots or lines inside them showing the existence of cells of smaller size similar to those near the boundary. The last picture in the plate is the photograph of a "reticular" cloud, or a cloud with "holes" with descending movement in the middle of each cell instead of the usual ascending movement. It was taken on 5th July 1939 at 1050 hrs. with the camera facing south at an altitude of 70°.

Fine cirro-cumulus gradually becoming coarser in structure.—(Plate VII).

(Date 2nd February 1939. Time 1525/1½m/1532½ hrs.).

Very often, cirro-cumulus cloud forms out of a clear sky and when first formed, it shows extremely delicate features. The six photographs of this series show the rapid transformation of the cells of such a delicate cirro-cumulus cloud into coarser cells. All the photographs, and especially the first two show a large-scale elongated honey-comb pattern of varying intensity superposed on the micro-cellular structure.

My thanks are due to Dr. K. R. Ramanathan for suggesting the work and for his continued interest and advice. I am also indebted to the Director-General of Observatories for permitting me to make use of the facilities available in the India Meteorological Department.

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2. **Prandtl, L.**—1936 *Proces—Verbaux des Seances de l'Assoc. de Meteorologie, Union geod. et geophys. Internationa e. Edin.* 171—202.

3. **Graham, A.**—Shear Patterns in an unstable layer of air, 1934 *Phil. Trans. Roy. Soc. A.*, **232**, 2445.

4. **Krishna Chandra,**—Instability of fluids heated from below, 1938 *Proc. Roy. Soc. A*, **164**, 231.

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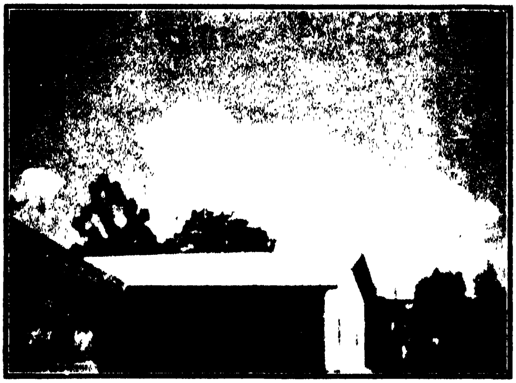
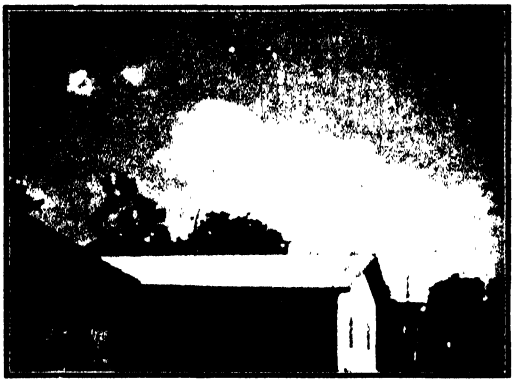
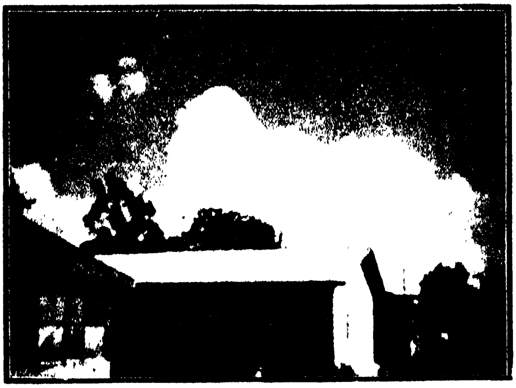
Plate I.



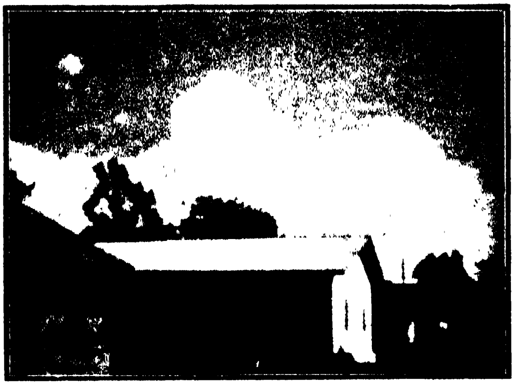
(a) 1645 Hrs.



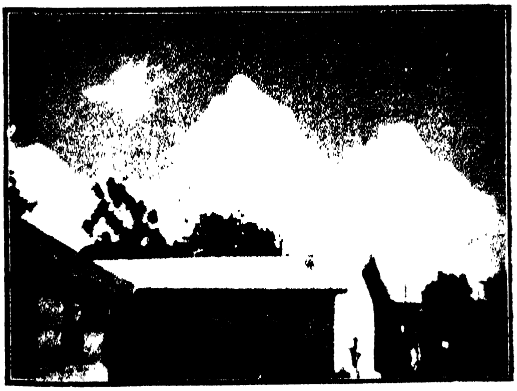
(b) 1646 Hrs.



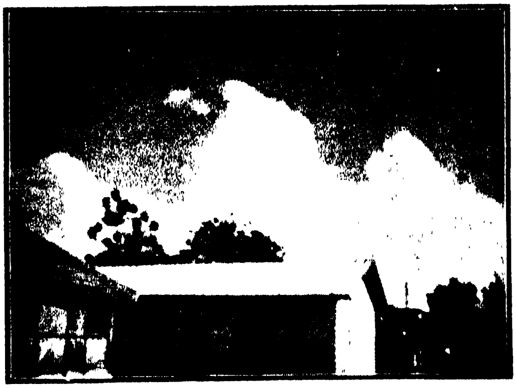
(c) 1647 Hrs.



(d) 1648 Hrs.



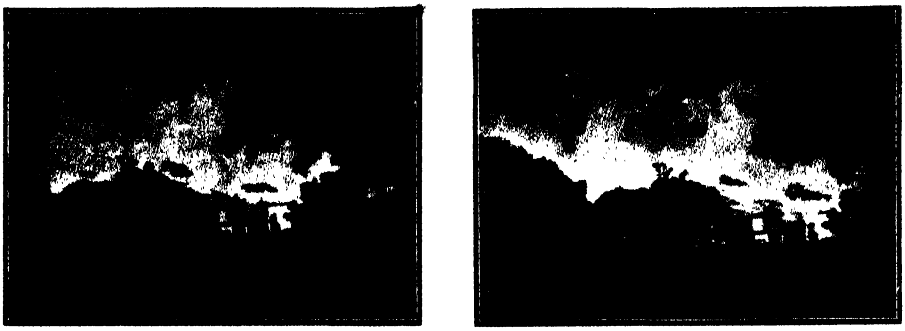
(e) 1649 Hrs.



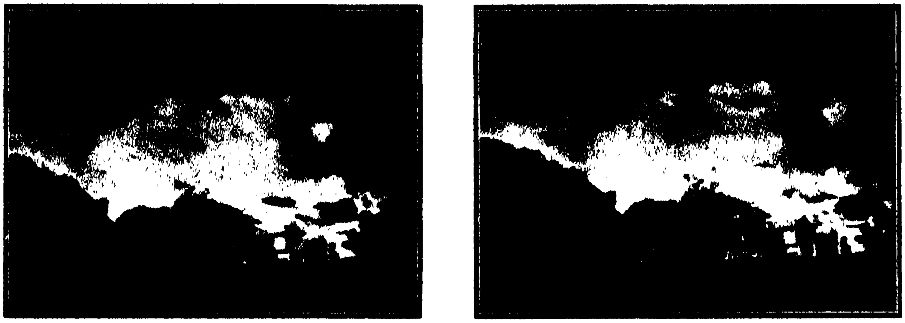
(f) 1650 Hrs.

Rising cumulus
11-5-40.

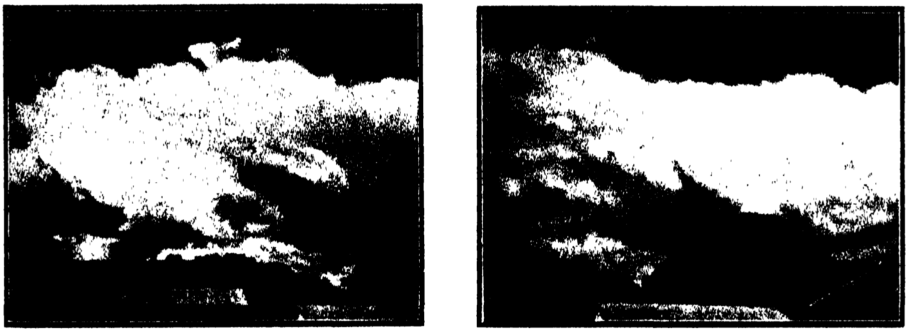
G P Z P. 1941.



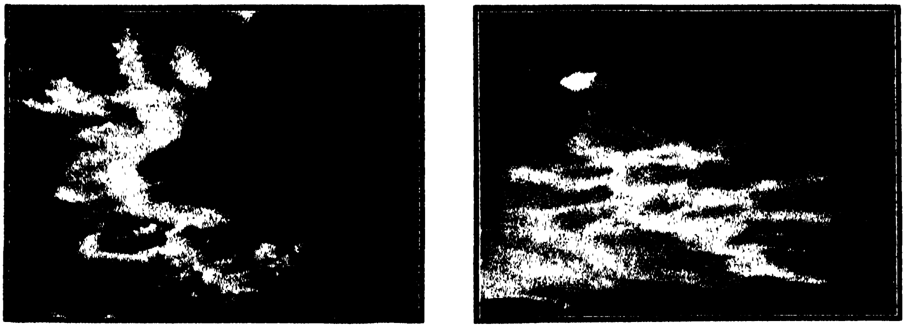
(a) 1615 Hrs. (b) 1616 Hrs.



(c) 1617 Hrs. (d) 1618 Hrs.



(e) 1655 Hrs. (f) 1656 Hrs.

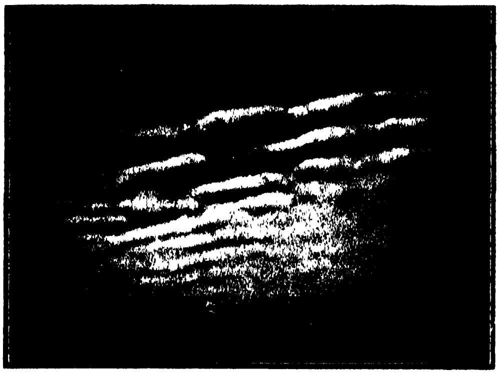


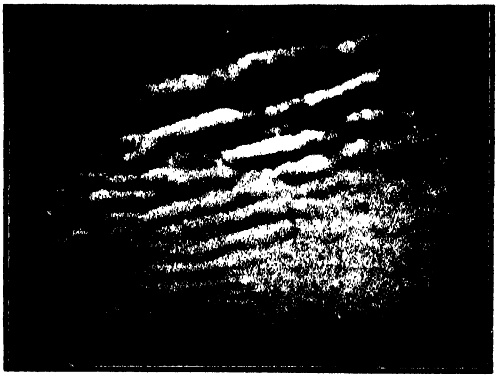
(g) 1800 Hrs. (h) 1825 Hrs.

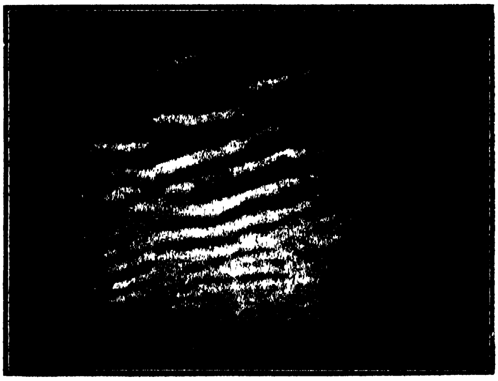
Large cumulus. Later spreading into strato-cumulus.
on 21-9-39.

G. P. Z. P. 1941.

Plate III.


(a) 0841 Hrs.


(b) 0842 Hrs.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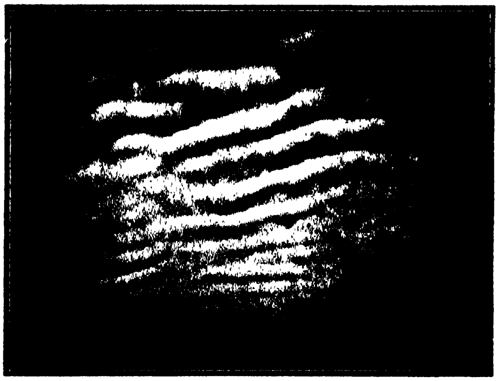
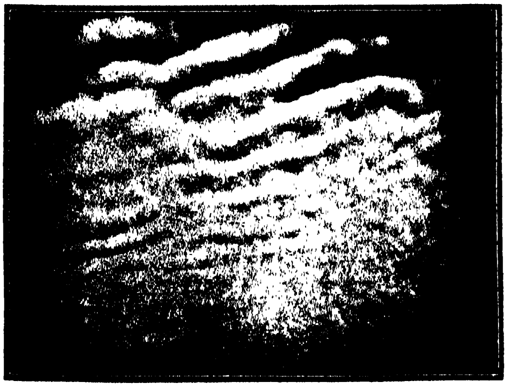
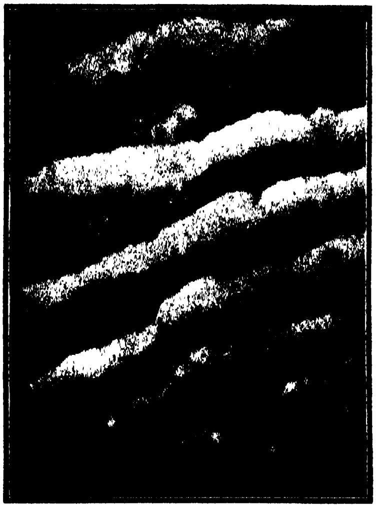

(d) 0844 Hrs.

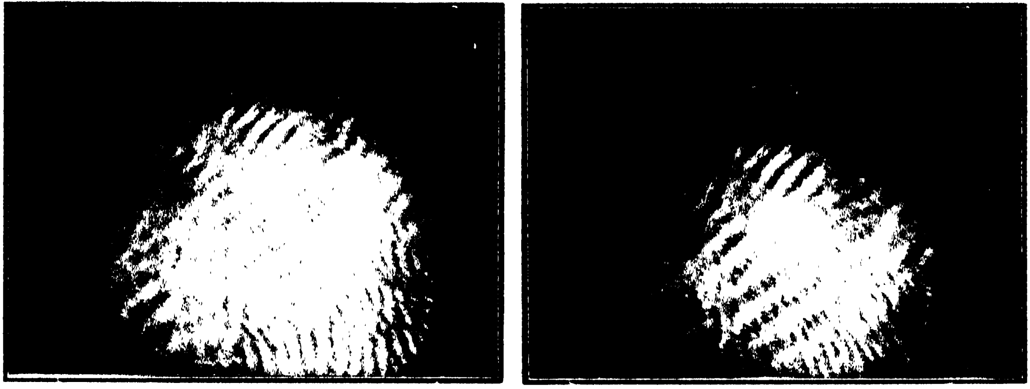

(e) 0845 Hrs.


(f) 0845 Hrs.

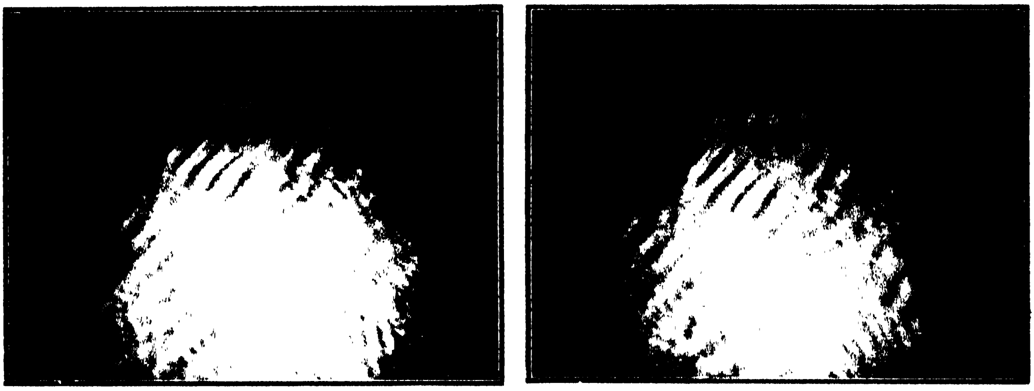
Transverse rolls in a stratiform cloud.

5-3-40.

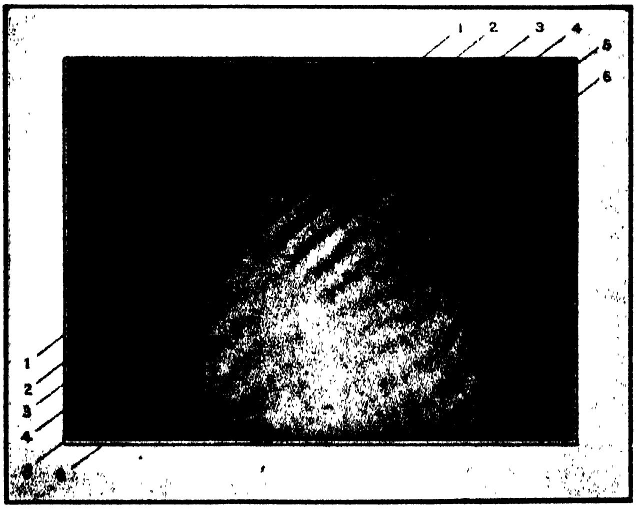
Plate IV.



(a) 1230 Hrs. (b) 1230½ Hrs.



(c) 1231 Hrs. (d) 1231½ Hrs.

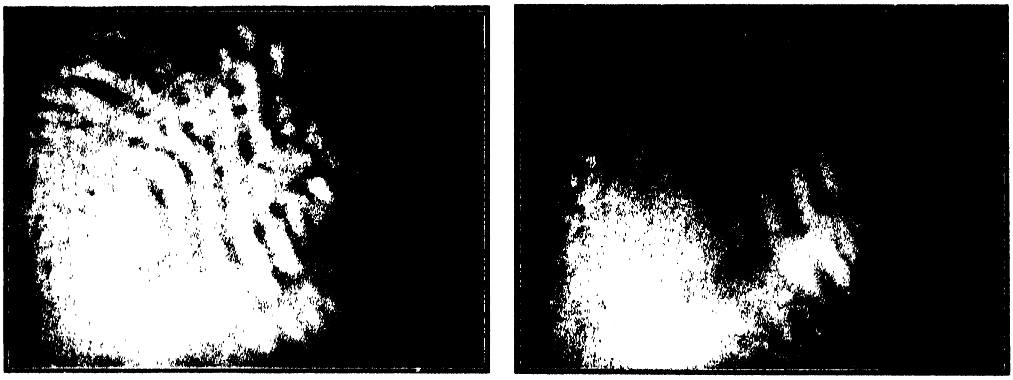


(e) 1232 Hrs.

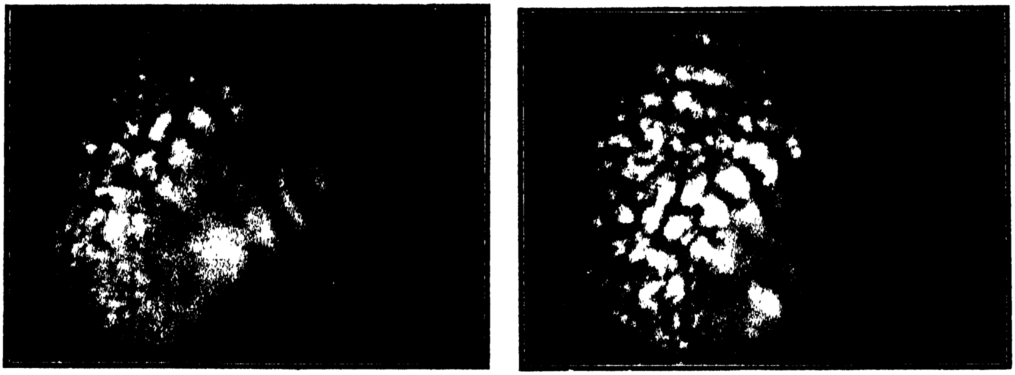
Transverse and longitudinal rolls in the same sheet of cloud. Note the doubling of the transverse rolls (marked 1 to 6 in e.)
5-4-40.

G. P. Z. P. 1941

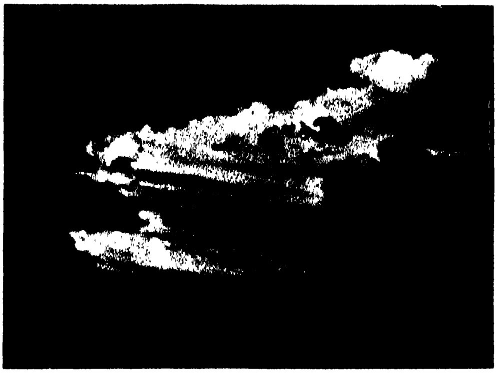
Plate V.



(a) 0750 Hrs. (b) 0752 Hrs.



(c) 0754 Hrs. (d) 0756 Hrs.

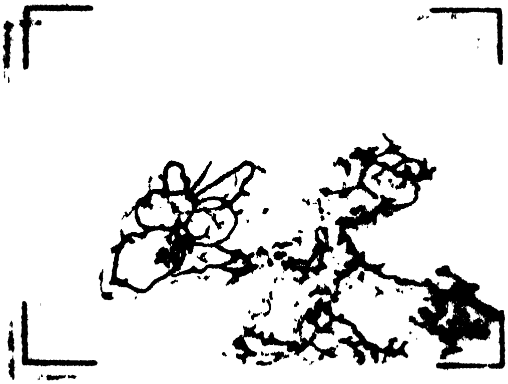


(e) 1849 Hrs.

(a) to (d) Transverse rolls and cells of alto-cumulus on 19-7-1939.
(e) Spread-out anvil of a cumulo-nimbus cloud on 30-3-39.

G. P. Z. P. 1941.

Plate VI.



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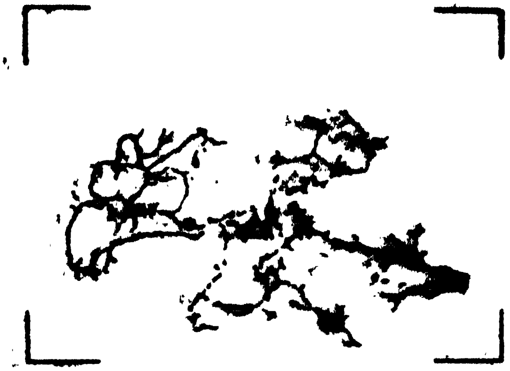

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3

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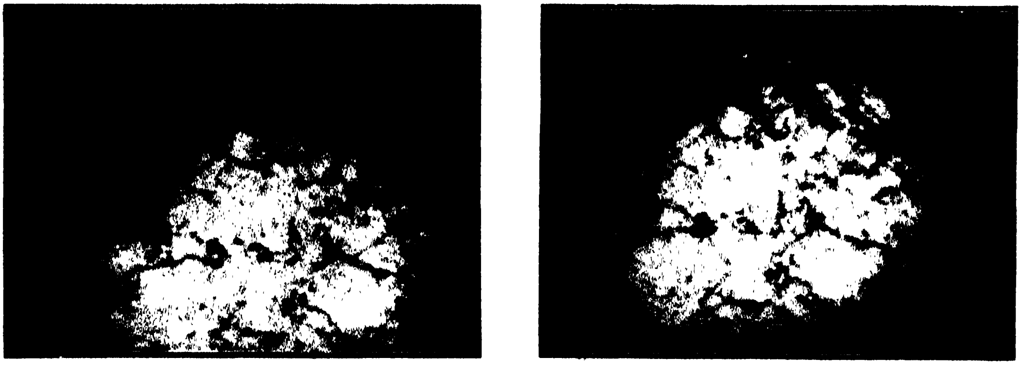
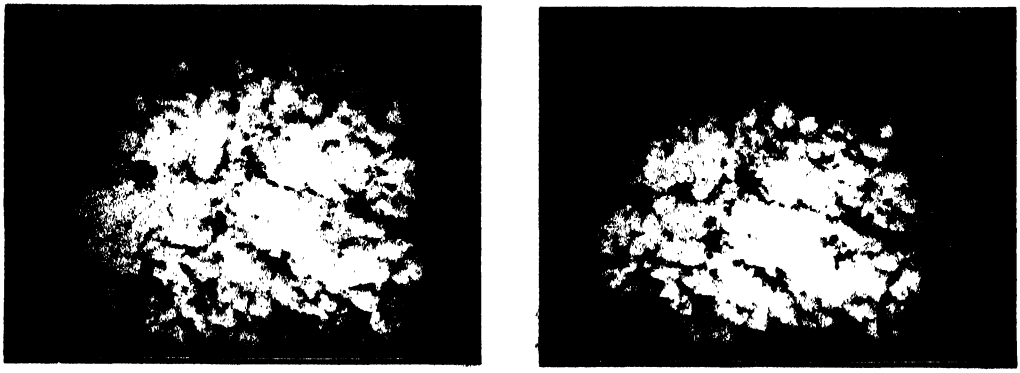
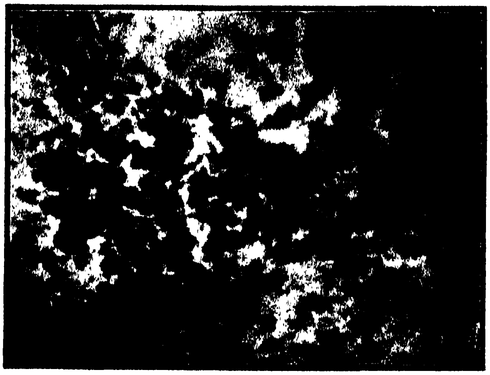
Plate VI.



(a) 1120 Hrs. (b) 1121 Hrs.



(c) 1122 Hrs. (d) 1123 Hrs.

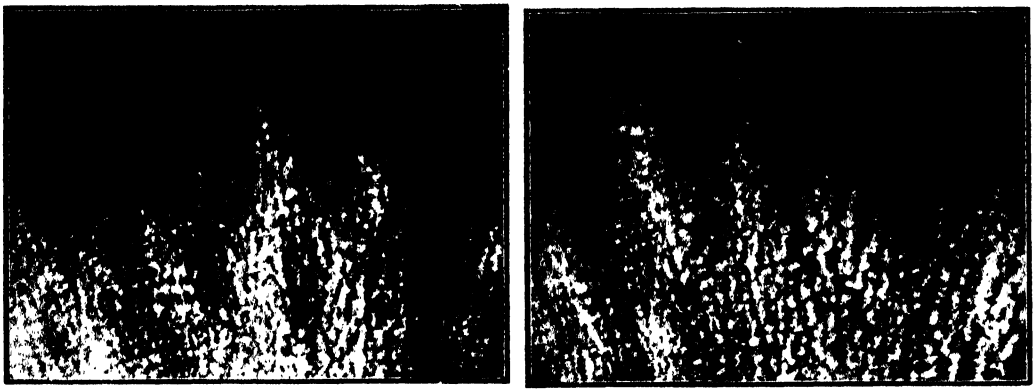


(e) 1150 Hrs.

(a) to (d).—Alto-cumulus broken up into flower-like polygonal cells. Note the very slow changes of form. 10-4-39.

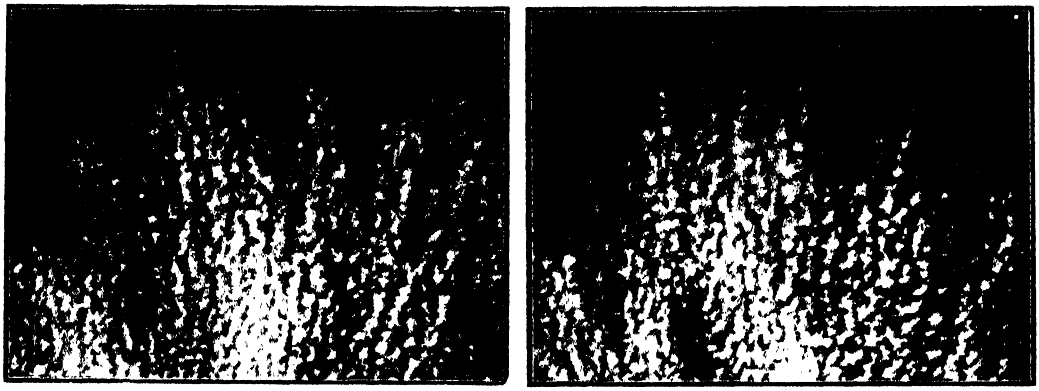
(e) "Reticular" cells of cirro-cumulus. 5-7-39.

Plate VII.



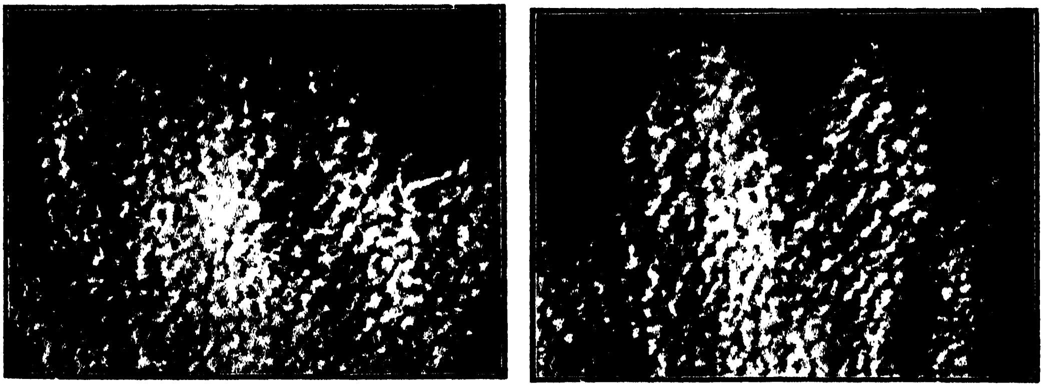
(a) 1525 Hrs.

(b) $1526\frac{1}{2}$ Hrs.



(c) 1528 Hrs.

(d) $1529\frac{1}{2}$ Hrs.



(e) 1531 Hrs.

(f) $1532\frac{1}{2}$ Hrs.

Fine cirro-cumulus cells gradually becoming coarser in structure.
2-2-39.

G. P. Z. P. 1941.

DGO. 19. VIII. 95.
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INDIA METEOROLOGICAL DEPARTMENT

SCIENTIFIC NOTES

Vol. VIII, No. 95.

Forecasting monsoon rainfall in Mysore

BY

V. DORAISWAMY IYER AND C. SESHACHAR.

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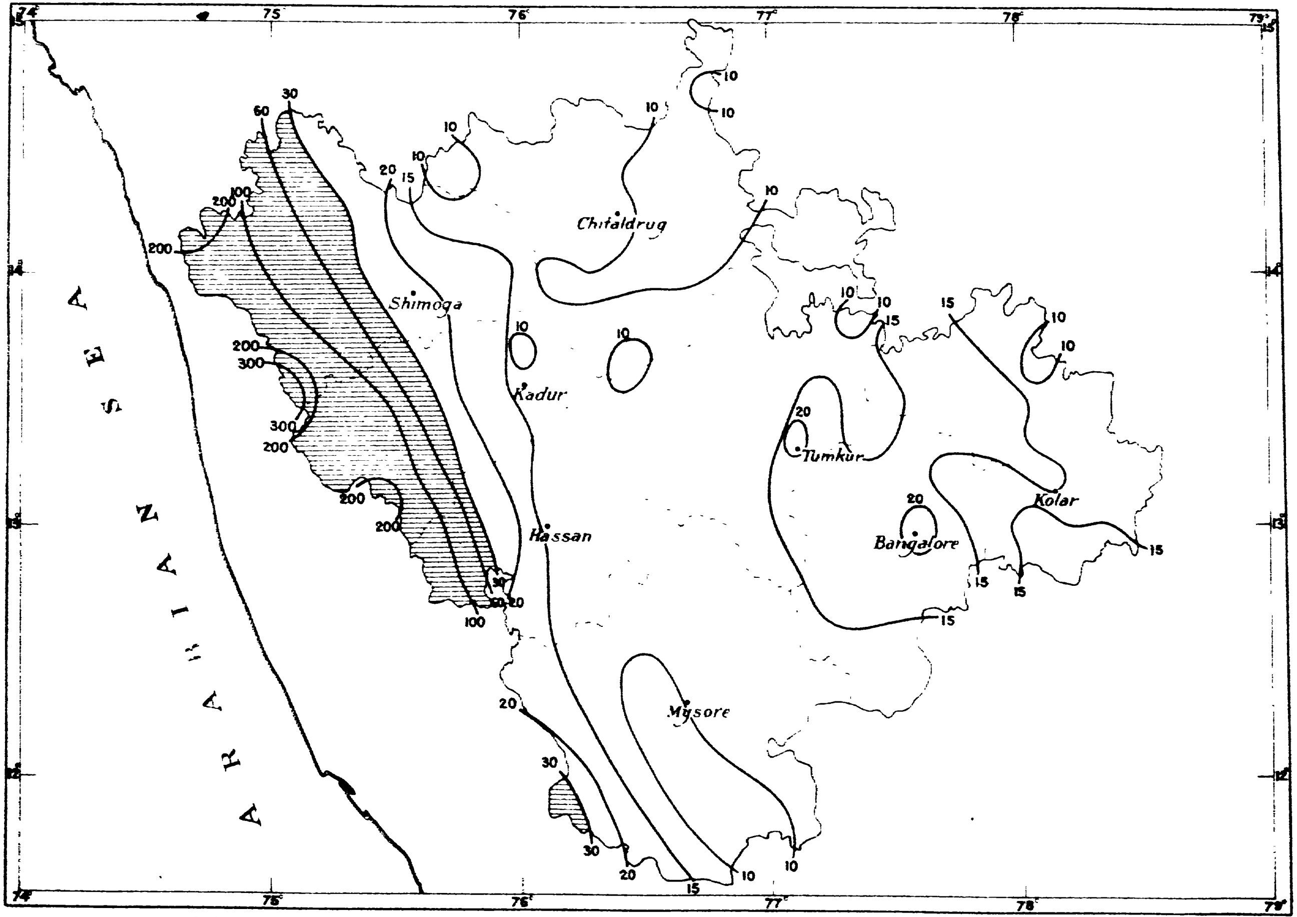

FIG. I. MAP OF MYSORE STATE SHOWING NORMAL RAINFALL (in inches) IN THE MONSOON MONTHS (JUNE TO SEPTEMBER)

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551·509·33 : 551·578·1 (54).

Forecasting monsoon rainfall in Mysore.

BY

V. DORAISWAMY IYER AND C. SESHACHAR.

Abstract.—A formula for forecasting the monsoon rainfall of the Mysore State as a whole was derived by Sir Gilbert Walker in 1921. In the present paper the State is divided into the two natural regions, *Malnad* and *Maidan*, and fresh sets of correlation coefficients are worked out for each of these regions. Formulae for forecasting the monsoon rainfall of June to September are derived for both the regions. For the *Maidan* region, a formula for forecasting the rainfall of the months September to November is also obtained.

Sir Gilbert Walker[1] worked out in 1921 the correlation coefficients of the rainfall of Mysore for the monsoon period, June to September, with the immediately preceding May pressure of the 16 pressure divisions of India adopted by him and with the data of other centres which he then used for obtaining a formula for forecasting the rainfall of India. The correlation coefficients then obtained are given below for ready reference.

Mysore rainfall (June to September) with —

1.	Pressure in May, division I	+·22
2.	 II	+·23
3.	 III	+·19
4.	 IV	+·24
5.	 V	+·20
6.	 VI	+·22
7.	 VII	+·29
8.	 VIII	+·31
9.	 IX	+·24
10.	 X	+·36
11.	 XI	+·27
12.	 XII	+·27
13.	 XIII	+·33
14.	 XIV	+·18
15.	 XV	+·29
16.	 XVI	+·22
17.	India pressure, May	+·28
18.	Mauritius pressure, May	—·19
19.	S. America pressure, ½ (April + May)	+·17
20.	Snowfall accumulation, end of May	—·09
21.	Zanzibar rain, May	—·39
22.	Seychelles rain, May	0
23.	Ceylon rain, May	+·08
24.	Java rain, (Oct. to Feb.)	—·46

Using India pressure (May), Zanzibar rain (May) and Java rain (October to February) he obtained the following formula[2].

[Mysore rain] = +·16 [India pressure] — ·26 [Zanzibar rain] — ·38 [Java rain].

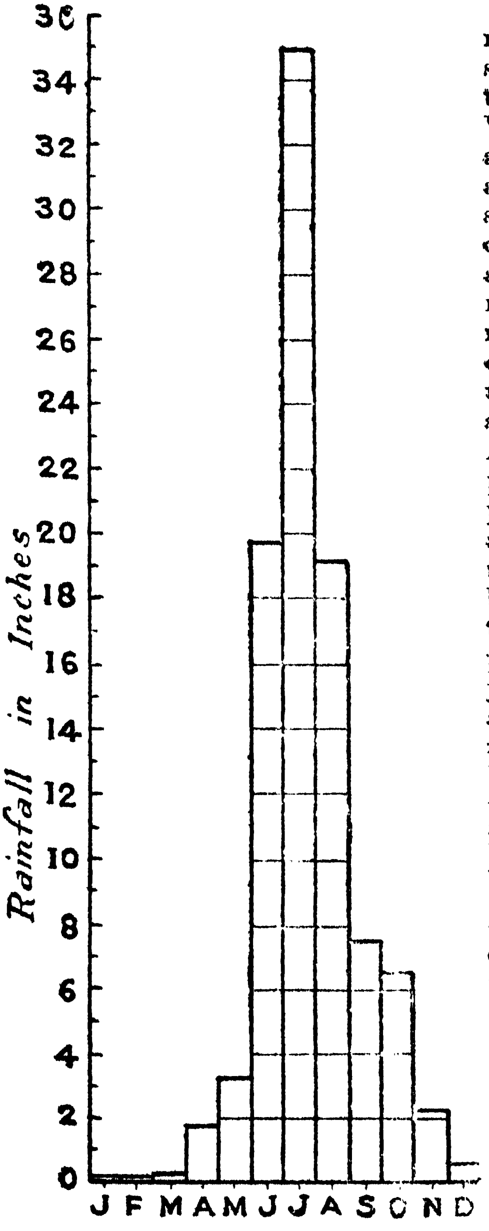
with a multiple correlation coefficient R = ·57.

The brackets [ ] denote proportional departures, *i.e.*, the ratio of the departures to their standard deviations.

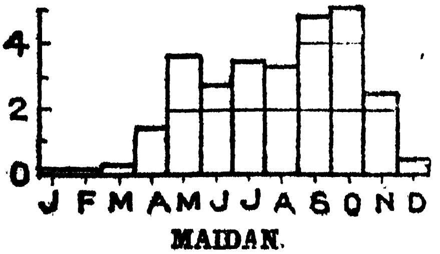
In obtaining these correlation coefficients the mean rainfall of the whole State of Mysore was used for the years 1875 to 1919. Owing to the paucity of raingauge stations in the earlier years, the rainfall of Mysore was based on the records of only eight district headquarters stations from 1875 to 1890; from 1891 however, the records of 74 stations were utilised, and the number rose to 77 in 1896 and remained the same during the rest of the period. As the rainfall data for the various stations were not subject to scrutiny before the year 1893 when the Mysore Meteorological Department was organised, it was considered desirable to utilise in this note rainfall data only from the year 1893.

Fig. 1 shows the distribution of normal rainfall over Mysore during the monsoon period. It will be seen that places on the western border of the state close to the Western Ghats record 300 inches or more and the seasonal total rapidly decreases as we proceed eastwards, the totals for some of the eastern stations being 10 inches or less. The narrow belt of hilly country adjoining the Western Ghats which is a region of evergreen forests and torrential rainfall is locally known as the *Malnad* or the land of hills and rain. The part of the state to the west of the isohyet of 30", shaded in *Fig. 1*, roughly corresponds to the *Malnad* region. The rest of the Mysore plateau is known as the *Maidan* or the plain country. Nearly 90 per cent. of the annual rainfall occurs in the monsoon months, June to September in the *Malnad*, but only about 50 per cent. of the annual total falls in the *Maidan* region in this period. July is the wettest month in the year for the *Malnad*, while September and October are the wettest months for the *Maidan* region. These facts are well brought out by the histograms of monthly normal rainfall for both the regions given in *Fig. 2*. Further, it is known that while a strong monsoon on the west coast is favourable for rain in the *Malnad*, it is during periods of weak monsoon, when the development of local convection is favoured, that good showers occur in the *Maidan* parts. The correlation coefficient between the monsoon rainfall of the *Malnad* and that of the *Maidan* is found to be only 0·31. That the *Malnad* and *Maidan* districts group themselves separately has also been shown by Ananthapadmanabha Rao after working out the inter-correlations between the rainfall of all the districts in Mysore[3]. It was therefore considered desirable to treat the *Malnad* and *Maidan* regions separately in our investigations in deriving fresh forecasting formulae for Mysore. This grouping has been justified by finding that the formulae obtained for the two regions have to be based on different sets of factors.

The following 9 taluk headquarters



MALNAD.



MAIDAN.

Fig 2. Histogram of Normal Monthly Rainfall.

stations have been selected to represent the *Malnad* area—

Shimoga District.—Thirthahalli, Hosanagar, Sagar and Sorab.

Kadur District.—Mudigere, Narasimharajapura, Koppa and Sringeri.

Hassan District.—Saklespur.

The average rainfall based on the rainfall data for 1893 to 1935 of the four monsoon months, June to September, for these stations is 85″. The other 68 taluk headquarters stations of the state have been grouped together to represent the *Maidan* region. The average rainfall of the monsoon season for this group of stations is 13″.

MALNAD RAIN, JUNE TO SEPTEMBER.

The correlation coefficients of the monsoon rainfall, June to September, of *Malnad* were worked out with pressure and temperature data of the centres used by Walker in investigations for monsoon forecasting; they are given in the following table. Using the method described in Scientific Note No. 37, para. 23, it is seen that for values of *n* ranging from 39 to 43, the probable values of the highest of 21 random coefficients between uncorrelated variables varies from 0·34 to 0·32, while the 95 per cent. values lie between 0·47 and 0·45[4]. In the table the only coefficient which can be considered significant is therefore that with India pressure in the contemporary quarter.

Correlation coefficients of Mysore (*Malnad*) rainfall June to September with—

	Years of Data.	Two quarters before Mysore, December to February.	One quarter before Mysore, March to May.	Contemporary quarter, June to August.
Pressure.				
1. Tokio	43	+·12	+·09	+·21
2. Central Siberia	40	+·03	+·20	—·15
3. Tashkent	42	—·15	—·09	—·12
4. N. W. India	43	—·07	+·24	—·28
5. India (whole)	43	—·02	+·24	—·51
6. Seychelles	41	+·13	—·07	—·01
7. Mauritius	42	+·22	+·01	0
8. Batavia	43	+·03	0	+·02
9. Port Darwin	43	+·12	—·04	+·03
10. Manila	40	+·16	+·15	+·02
11. S. E. Australia	41	+·17	—·07	—·12
12. Samoa	41	—·15	—·23	—·04
13. Honolulu	42	+·13	—·03	+·09
14. San Francisco	43	+·06	—·01	+·02
15. Charleston S. C.	43	—·02	—·03	+·14
16. S. America	43	—·09	+·21	+·18
17. Cape	43	+·09	—·18	+·19
18. Vienna	39	—·04	—·04	—·13
19. Stykkisholm	43	—·03	—·03	0
Temperature.				
20. Dutch Harbour	42	—·10	+·02	+·03
21. South Orkneys	27	—·10	+·19	+·11

The correlation coefficient of *Malnad* rain with India pressure, May, which has been used by Walker, in his Mysore forecast formula, is found to be +·39, while with South American pressure ½ (April + May), used in the monsoon forecasts of the Peninsula and Northwest India, the C.C. is +·37.

It is found that years of sunspot maxima are generally associated with years of deficient rainfall in the *Malnad*, while years with minimum number of sunspots have an excess of rainfall[6]. The C.C. between the annual sunspot number and the monsoon rainfall of the same year is —·39, while that with the rainfall of the following year is —·35.

Correlations of *Malnad* rains were also worked out with the snowfall accumulation on the Western Himalayas at the end of May as well as with the rainfall of the regions which have shown relationship with Indian rainfall. They are given below and the C.C. with Java is promising.

	Years of data.	C. C.
Snowfall accumulation in the western Himalayas (end of May) ..	43	+·07
Rainfall—		
S. Rhodesia (Oct. to April)	37	—·10
Java (October to February)	43	—·32
Amini Divi (May)	39	—·23
Minicoy (May)	41	—·08
Zanzibar District (May)	43	—·21

Using the four factors, India pressure (May), South American pressure ½ (April + May), Sunspot numbers (previous year) and Java rain (October to February) the following table of C.Cs. is formed.

	India Pressure.	S. American pressure.	Sunspot numbers.	Java rain.
Malnad rain	+·39	+·37	—·35	—·32
India pressure	..	+·42	—·23	—·22
S. American pressure	..	..	+·09	—·03
Sunspot numbers	..	..	..	+·17

This gives the formula—

[*Malnad* rain] = +·13 [India pressure] +·34 [S. American pressure] —·31 [Sunspot numbers] —·23 [Java rain].

with the resulting multiple correlation coefficient R = ·60.

The values calculated with the above formula and the actual values are plotted in *Fig. 3*.

The significance of this multiple correlation coefficient may be tested by Wishart's table[6]. The 5% and 1% values of R according to this table (N = 43 n = 4) are 0·47 and 0·54 respectively. Hence the value of R is significant. It should however be noted that Wishart's table is not strictly applicable to the above result in the obtaining of which selection had played a prominent part.

The true test of the regression formula lies in its performance in future. If at the end of some years, say ten, the values calculated from the regression formula should have a C.C. with the actual values which is positive and significant, it can be said to have shown a good performance. Meanwhile some idea of its future performance may be gathered by testing the performance of the selected independent variates by past data. For this purpose a regression formula, using data of the selected factors for the period 1893 to 1914 only was evolved; this gave a multiple coefficient R = ·72. The C.C. between the values calculated with the above formula and the actual values for the years 1915 to 1935 was found to be only 0·31 with a probable error of ±·14, the 5% value for the case in which ρ = 0 being 0·43. This shows that although the performance of the selected factors has not been consistently satisfactory in the past, the fact that the latter coefficient is positive in sign enables us to assert that the factors selected by us retain a certain degree of consistency.

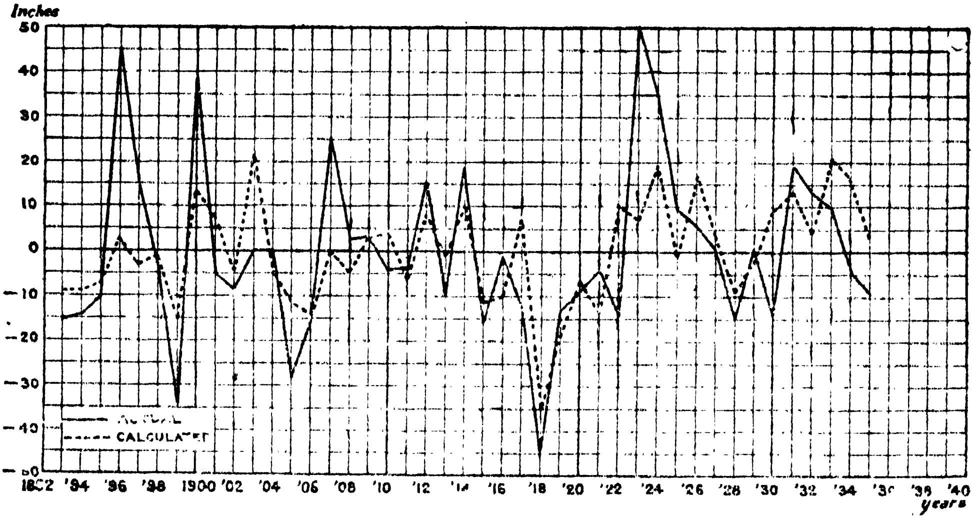


Fig 3. Malnad Rainfall, (June to September).

MAIDAN RAIN, JUNE TO SEPTEMBER.

The correlation coefficients between *Maidan* rain, June to September, and pressure and temperature centres for the contemporary quarter and the two preceding quarters are given in the table below. As Seychelles and Mauritius had similar coefficients both in the contemporary and the preceding quarter, and as both are in the south Indian Ocean they were combined into one factor and the C.Cs. with this factor also worked out. The probable values of the highest of 23 random coefficients between uncorrelated variables, for values of *n* ranging from 39 to 43 varies from ·35 to ·33, while the 95% values lie between ·47 and ·45[4]. It will be seen from the table that there are no significant correlations in the second preceding quarter. In the quarter March to May there are three significant coefficients, while in the contemporary quarter there are seven such coefficients.

Correlation coefficients of Mysore (*Maidan*) rainfall June to September with—

	Years of data.	Two quarters before Mysore, December to February.	One quarter before Mysore, March to May.	Contemporary quarter, June to August.
Pressure.				
1. Tokio	43	+·05	—·21	—·12
2. Central Siberia	40	+·11	+·44	—·30
3. Tashkent	42	—·08	—·19	—·13
4. N. W. India	43	+·04	+·33	+·11
5. India (whole)	43	+·02	+·29	—·06
6. Seychelles	41	—·07	—·23	—·49
7. ½ (Seychelles + Mauritius)	41	+·01	—·29	—·50
8. Mauritius	42	+·07	—·24	—·46
9. Batavia	43	+·08	—·06	—·40
10. Port Darwin	43	+·30	+·05	—·41
11. Manila	40	+·13	+·03	+·39
12. S. E. Australia	41	+·18	—·13	—·24
13. Samoa	41	—·17	0	+·29
14. Honolulu	42	+·22	+·41	+·30
15. San Francisco	43	—·03	+·09	—·08
16. Charleston S. C.	43	—·17	—·07	—·21
17. S. America	43	—·03	—·04	+·31
18. Cape	43	+·10	—·11	0
19. Vienna	39	—·25	—·22	—·26
20. Stykkisholm	43	+·04	+·08	+·27
21. Southern Oscillation	38	—·29	—·01	+·46
Temperature.				
22. Dutch Harbour	42	—·09	—·04	—·11
23. South Orkneys	27	—·05	—·02	+·10

Coefficients with the rainfall of different regions and with the snowfall accumulation on the western Himalayas at the end of May are given in the following table.

	Years of data.	C. C.
Snowfall accumulation in the western Himalayas, end of May ..	43	+·01
Rainfall—		
South Rhodesia (October to April)	37	—·28
Java (October to February)	43	—·25
Amini Divi, May	39	—·05
Minicoy, May	41	+·13
Zanzibar District, May	43	—·19

For the three centres, Central Siberia, Northwest India and Honolulu, which have significant correlations in the preceding quarter, March to May, as well as for ½ (Mauritius + Seychelles), correlation coefficients were worked out for the individual months, March, April and May and for the months April and May combined. In the case of Central Siberia C.Cs. were worked out for January and February also. Similarly for Vienna which has sustained relationships in all the three quarters the C.Cs. for individual months January to May were worked out. The values are given below.

	Mysore *Maidan* rain with—					
	January.	February.	March.	April.	May.	½ (April + May).
Pressure. 1. N. W. India	..	..	+·09	+·30	+·26	+·35
2. Central Siberia ..	+·14	+·08	+·44	+·06	+·08	..
3. Honolulu	..	..	+·26	+·35	+·32	+·38
4. ½ (Mauritius + Seychelles)	..	..	—·05	—·14	—·28	—·27
5. Vienna	—·24	—·17	—·08	+·04	—·37	..

It will be seen that the C.Cs. with the individual months March, April and May, are generally less than the C.C. for the quarter as a whole, a feature which is often noticed. Hence in the case of the first four factors the C.C. for the quarter March to May was selected as more suitable for deriving the forecast formula. The C.C. with Vienna pressure in the month of May is however considerably higher than for the quarter as a whole, and hence this month was selected. With these five factors the following table of C.Cs. is formed.

—	Central Siberia pressure (March to May).	Honolulu Pressure (March to May).	Vienna Pressure (May.)	N. W. India pressure (March to May).	½ (Mauritius+Seychelles) pressure (March to May).
Maidan rain	+·44	+·41	—·37	+·33	—·29
Central Siberia	..	+·35	—·05	+·22	—·06
Honolulu	..	..	—·18	+·10	+·18
Vienna	..	..	..	+·06	+·01
N. W. India	..	..	..	..	+·04

With these we get the following regression equation.—

[*Maidan* rain] = +·24 [Central Siberia pressure] +·30 [Honolulu pressure] —·32 [Vienna pressure] +·28 [N. W. India pressure] —·34 [Mauritius + Seychelles pressure].

with the resulting multiple correlation coefficient R = ·73.

As data for Central Siberia are not available after 1932, this factor had to be omitted and with the other four factors the following regression equation was formed.

[*Maidan* rain] = +·39 [Honolulu pressure] —·32 [Vienna pressure] +·33 [N. W. India pressure] —·37 [Mauritius + Seychelles pressure].

with the resulting multiple correlation coefficient R = ·70.

Thus the omission of Central Siberia has not led to any appreciable decrease in the multiple C.C. The values calculated with the above formula and the actual values are plotted in *Fig. 4.*

It is seen from Wishart's table[6] that the 5% and 1% values of R, (N = 41, n = 4) are ·48 and ·55 respectively. Hence the value of R is significant.

In order to form an idea of its future performance a regression formula was evolved, as in the case of *Malnad* rain, using data of the selected factors for the years 1893 to 1914 only. This gave a multiple C.C. of ·73. The C.C. between the values calculated with the above formula and the actual values for the years 1915 to 1935 was found to be +0·57 with a probable error of ±·11. This value is significant, the 5% value for significance being ·43. Hence the performance of the selected factors has been satisfactory in the past, and may be expected to show consistency in the future also.

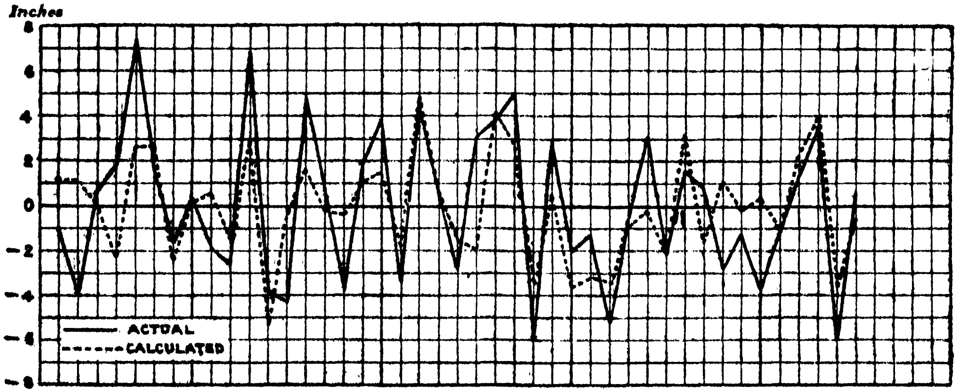


Fig 4. Maidan Rainfall, (June to September).

MAIDAN RAIN, SEPTEMBER TO NOVEMBER.

Rainfall over the *Maidan* region from September to November is very important from the agricultural point of view. Nearly half the rain of the *Maidan* is received during these months and the tanks in the Mysore State get filled up in this period. Hence a foreknowledge of the probable amount of rainfall of these months is of importance in the agricultural economy of the State. Correlation coefficients of the rainfall of this period were accordingly worked out with the pressure and rainfall of the immediately preceding quarter and with other elements detailed in the table below.

Correlation coefficients of Mysore (Maidan) rainfall September to November with—

	Years of data.	One quater before, June to August.
Pressure.		
1. Central Siberia	40	—·15
2. Northwest India	43	+·08
3. Seychelles	41	—·48
4. Mauritius	42	—·37
5. Batavia	43	—·36
6. Port Darwin	43	—·25
7. Southeast Australia	41	..
8. Samoa	41	+·07
9. Honolulu	42	+·05
10. South America	43	+·04
11. Southern Oscillation	..	+·24
Rain.		
12. Mysore (*Maidan*)	43	+·12
13. Mysore (*Malnad*)	43	—·31
14. Java (Oct. to Feb.)	43	—·19
15. South Rhodesia (Oct. to April)	37	—·20

The probable value of the highest of 15 random coefficients between uncorrelated variables is ·31, while the 95% value is ·44, n being equal to 42[4]. It will be seen from the table that the C.Cs. with three of the four centres in the South Indian Ocean are above the random value and that one of these exceeds even the 95% value. All the four centres were taken together as representing the pressure over the South Indian Ocean, and the C.C. with the mean of the four stations, Batavia, Port Darwin, Seychelles and Mauritius was found to be —·46; this may be taken to be significant.

It has been observed that high pressure over northern India and low pressure over the south of the Peninsula in July are favourable for rainfall in Mysore during August and September, the correlation coefficients with Walker's pressure divisions II to VI in northern India being +·35, +·35, +·29, +·26 and +·35 respectively, and with pressure divisions XIV to XVI in the south of the Peninsula being —·37, —·23 and —·39 respectively[7]. It was therefore considered that the difference of pressures in the two regions *i.e.*, the gradient of pressure between south Peninsula and north India would yield a useful relationship with *Maidan* rain, September to November. The mean pressure (A) of the four stations, Madras, Bangalore, Mangalore and Trivandrum was taken to represent the pressure divisions XIV to XVI, and the mean pressure (B) of the five stations Mandalay, Calcutta, Patna, Lucknow and Lahore to represent the pressure divisions II to VI. With A—B, the pressure gradient between the south of the Peninsula and northern India we get a C.C. of —·40. Using the same stations, the pressure gradient during August yields a C.C. of —·46, while the pressure gradient in both the months combined gives a C.C. of —·53.

The westerly upper winds which set in over the south of the Peninsula with the commencement of the southwest monsoon extend up to 4 kms. in July and August. The strength of these winds in these months may be expected to give some indication of the activity of the monsoon in the subsequent months. Hence the mean wind velocities, irrespective of direction, of the upper winds over Bangalore from 2 to 4 kms. were correlated with the *Maidan* rainfall September to November. The coefficients obtained are—

July 2 kms. —·41, 3 kms. —·40, and 4 kms. —·02,
August 2 kms. —·39, 3 kms. —·41, and 4 kms. —·11.

With the means of the velocities at 2, 2·5 and 3 kms. the coefficients were July —·38, August —·43 and July + August —·48. As these coefficients are based on 20 years' data, it is seen that the last two coefficients will be just significant in the long run.

The factors that may be selected from the above for deriving a forecasting formula are—

(1) *Malnad* rain June to August,
(2) Bangalore upper winds 2 to 3 kms, July and August,
(3) India pressure gradient July and August, and
(4) South Indian Ocean pressure, June to August.

As Bangalore upper winds are available only from 1915, the coefficients of the other factors were also worked out for the same period in order to obtain coefficients for a uniform period for all the factors. The following table of C.Cs. is then formed.

	Malnad rain June to August.	Bangalore upper winds 2 to 3 kms. ½ (July + August).	India pressure gradient (South—North) July and August.	South Indian Ocean pressure June to August.
Maidan rain	—·58	—·48	—·53	—·38
Malnad rain	..	+·30	+·16	+·14
Bangalore upper winds	..	..	+·37	+·52
India pressure gradient	..	..	..	+·68

This gives the formula—

[*Maidan* rain] = —·45 [*Malnad* rain] —·24 [Bangalore upper winds]
—·44 [India pressure gradient] +·11 [South Indian Occean pressure]
with the resulting multiple correlation coefficient R = ·75.

If we omit South Indian Ocean Pressure, as it has high cross coefficients with two of the other factors, and as its contribution to the multiple correlation coefficient is negligible and negative, we get the following formula—

[*Maidan* rain] = —·46 [*Malnad* rain] —·20 [Bangalore upper winds]
—·38 [India pressure gradient]
with the resulting multiple correlation coefficient R = ·75.

The value of the multiple correlation coefficient is thus not altered by the omission of South Indian Ocean pressure.

It is seen from Wishart's table* that the 5% and 1% values of R, (N = 21, n = 3), are 0·56 and 0·65 respectively. Hence the value of R is significant.

The number of years is too small to permit of any tests of performance.

The values calculated with the above formula and the actual values are plotted in *Fig. 5.*

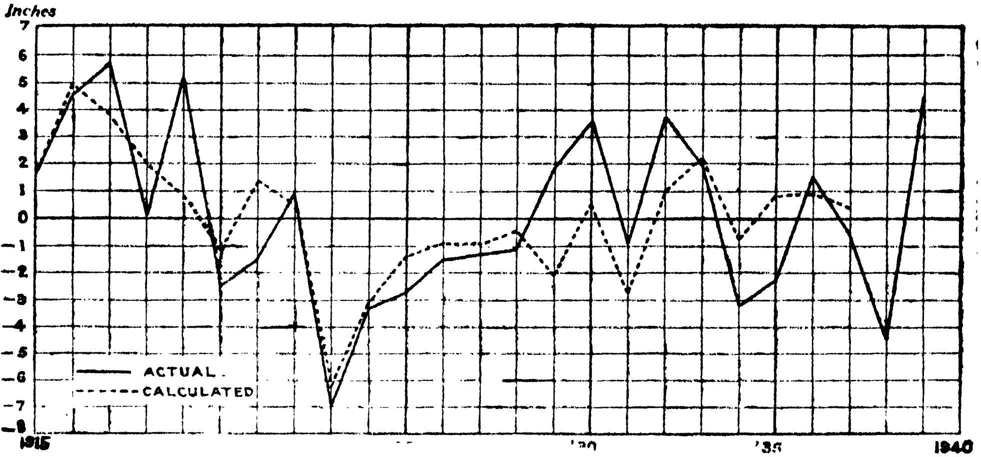


Fig 5. Maidan Rainfall, (September to November).

We are grateful to the Director General of Observatories for having allowed us to use the data available in the Meteorological Office, Poona.

Note by S. R. Savur.

The Performance Test explained in some detail in S. R. Savur's paper* requires a correction when applied to simple or multiple correlation coefficients.

It was stated in that paper that the test correlation coefficient should be considered as a random correlation coefficient and the usual test of significance should be applied to it. This, however, does not take into account the fact that the test correlation coefficient, in order to be considered significant, should, in addition, have the same sign as that of the original coefficient, although in actual practice the test is applied only after it is found from inspection that the two correlation coefficients have the same sign. To embody this fact in the test the following modification has to be made.

---

* S. R. Savur: Ind. Jour. Phy., Vol. VII, Pt. I, 1932, pp. 27—34.

Suppose P is the level of significance selected by us. Then the level of significance actually used for the test correlation coefficient should be 2 P. It is unfortunate that this point of view did not occur to the writer previously.

Applying this (rectified) test to the test correlation coefficients obtained on p. 122, 125 in the present paper, we see that the number of years on which the test r's are based is 21. Using 5% as our level of significance we find that the test r's should not be numerically less than ·37 in order to be considered significant. The actual value of the test r for Malnad is less than this value and that for Maidan is above it. The conclusions arrived at in the paper are not, however, affected.

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INDIA METEOROLOGICAL DEPARTMENT

SCIENTIFIC NOTES

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Frequency of thundery Conditions at Bombay compared with those at some other Stations in India

BY

M. W. CHIPLONKAR.

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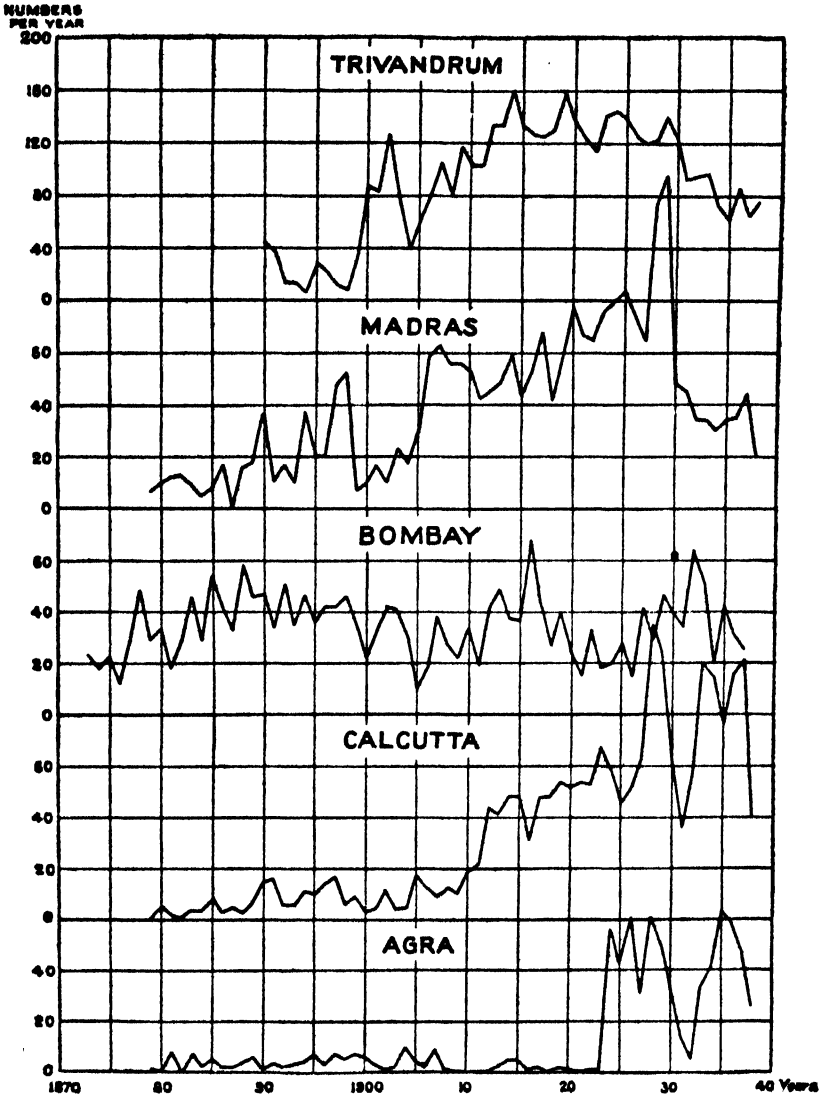
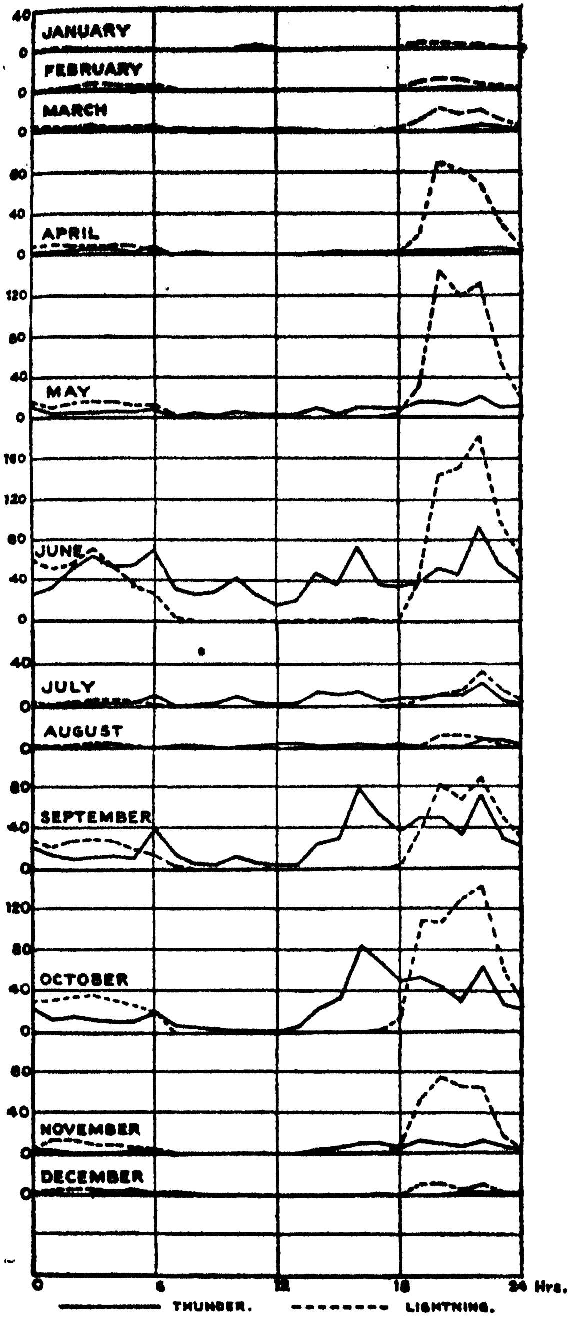

NUMBERS PER YEAR
TRIVANDRUM
200
160
120
80
40
0
MADRAS
60
40
20
0
BOMBAY
60
40
20
0
CALCUTTA
60
40
20
0
AGRA
40
20
0
1870
80
90
1900
10
20
30
40 Years

Fig. 2.



HOURLY FREQUENCY OF THUNDER AND LIGHTNING AT BOMBAY

Fig. 1.

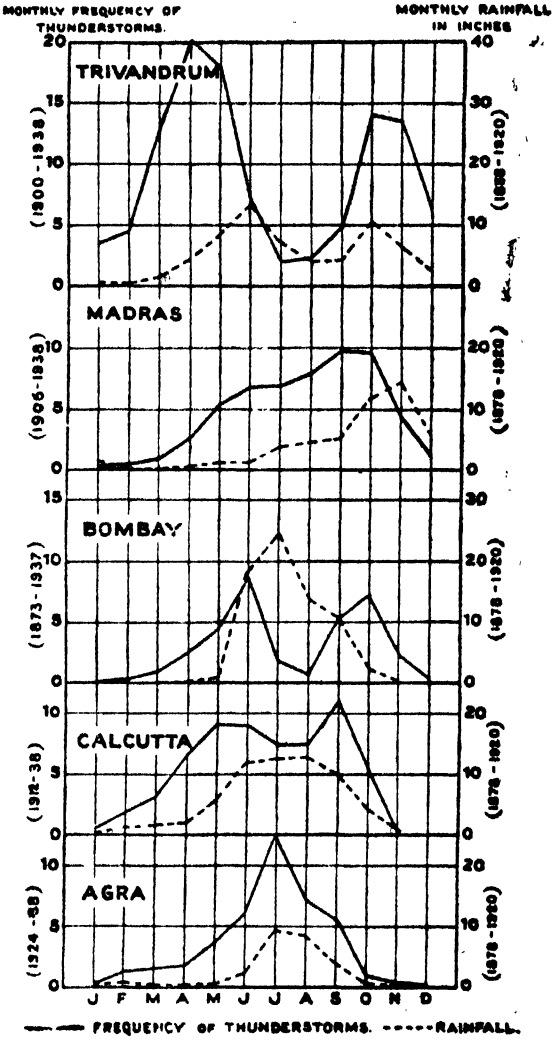


Fig. 3.

TABLE II—*concld.*

Station. / Year.	Trivandrum.	Madras.	Bombay.	Calcutta.	Agra.
1923	141	76	18	68	1
24	144	80	20	59	56
25	138	83	28	46	43
26	125	73	15	52	61
27	119	64	42	63	31
28	122	117	29	115	61
29	140	137	47	104	50
30	122	48	39	59	33
31	93	45	34	36	14
32	95	34	64	57	5
33	96	34	51	100	33
34	73	30	20	94	41
35	63	34	43	77	63
36	86	35	31	96	58
37	65	44	25	102	47
38	56	20	..	40	26

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TABLE II—*contd.*

Station. / Year.	Trivandrum.	Madras.	Bombay.	Calcutta.	Agra.
1898	9	53	46	6	5
99	36	7	35	9	7
1900	87	10	22	3	6
1901	84	17	32	5	3
2	127	10	42	12	1
3	80	23	41	4	2
4	39	17	30	5	10
5	63	30	10	18	4
6	80	59	19	13	2
7	106	63	38	9	9
8	79	56	27	13	1
9	117	56	22	10	0
10	103	53	34	19	0
11	104	42	19	22	0
12	133	45	42	44	0
13	133	49	49	41	2
14	160	59	37	48	5
15	133	43	36	48	5
16	126	53	68	31	1
17	125	68	43	48	2
18	130	41	27	48	0
19	158	59	40	54	2
20	137	77	25	52	1
21	124	67	15	54	0
22	114	65	34	53	1

TABLE II.

The number of days of Thunder and Lightning activity at different stations in India.

Station. / Year.	Trivandrum.	Madras.	Bombay.	Calcutta.	Agra.
1873	..	..	23	..	..
74	..	..	18	..	..
75	..	..	23	..	..
76	..	..	12	..	..
77	..	..	29	..	..
78	..	..	49	..	..
79	..	7	29	0	1
80	..	10	34	5	0
81	..	12	18	2	8
82	..	13	29	1	[illegible]
83	..	10	46	4	7
84	..	5	29	4	2
85	..	8	54	8	5
86	..	17	42	3	2
87	..	0	33	5	2
88	..	16	58	3	4
89	..	18	46	7	6
90	45	37	47	15	1
91	37	11	34	16	3
92	14	17	51	6	2
93	14	10	35	6	3
94	6	37	47	11	4
95	29	20	36	10	7
96	23	20	42	14	3
97	13	48	42	17	7

lightning were recorded at Bombay during the period 1873 to 1937.

(L. M. T.)

12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24	Total number of night hours of thunder or lightning and their ratio.	
..	..	..	..	..	..	1	..	..	..	..	..	2	1/12
..	..	..	..	..	..	5	6	4	3	1	1	25	
..	..	..	..	..	..	1	1	2	1	..	..	6	1/10
..	..	..	..	..	..	7	10	9	5	3	..	60	
2	1	..	..	..	..	..	..	2	5	3	3	26	1/4·4
..	..	..	..	..	2	10	22	17	20	11	4	113	
..	1	3	2	1	..	3	3	4	5	5	3	51	1/7
..	..	..	..	..	2	19	89	83	69	31	8	347	
3	8	3	10	9	8	15	15	13	20	10	12	121	1/4·8
..	..	..	..	..	4	29	144	119	131	55	17	577	
20	47	36	72	37	34	38	52	45	93	58	27	641	1/1·5
1	..	1	2	1	1	37	143	151	181	98	61	950	
4	14	12	14	5	8	8	11	11	22	6	2	86	1/1·4
..	..	..	..	..	2	6	12	15	35	15	6	118	
4	1	2	3	1	3	1	2	1	7	6	..	126	1/1·9
..	..	..	..	..	..	1	12	12	8	2	..	349	
4	26	30	80	54	37	51	50	33	73	31	23	365	1/1·3
..	..	..	..	..	4	37	83	69	89	52	29	562	
6	24	34	85	60	51	54	45	35	65	28	15	326	1/2·3
..	..	..	..	1	14	110	108	130	144	62	32	769	
..	4	6	10	10	6	13	10	7	12	8	5	64	1/5
..	..	..	..	..	9	55	75	66	65	18	4	339	
..	..	..	..	1	..	..	..	1	1	1	1	8	1/7
..	..	..	..	..	1	10	10	5	9	3	1	57	
43	126	126	276	187	147	185	189	154	304	156	91		
1	0	1	2	2	39	326	714	680	759	351	162		
0·7	2·0	2·0	*4·1*	2·9	2·3	2·8	2·9	2·4	*4·7*	2·4	1·4		
0·0	0·0	0·0	0·0	0·0	0·6	5·0	11·0	10·5	*11·8*	5·4	2·5		

TABLE I.—*The total number of hours during which thunder and*

Month.	Thunder (T) or Lightning (L).		Hours											
			0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12
Jan. ..	T		..	..	..	..	..	1	..	..	..	..	2	..
		L	1	1	1	1	1	..	..	..	..	..	..	..
Feb. ..	T		..	..	..	..	1	..	1	..	..	..	..	..
		L	2	4	7	5	4	4	1	..	..	..	..	..
March ..	T		2	2	2	3	3	1	..	2	2	2	1	1
		L	5	5	6	4	4	5	..	..	..	..	..	..
April ..	T		2	5	5	6	3	7	1	2	1	..	..	..
		L	10	9	8	9	9	3	1	..	..	..	..	..
May ..	T		4	5	6	7	6	8	2	5	1	5	2	3
		L	11	14	16	16	12	13	3	..	..	..	..	..
June ..	T		33	52	64	54	55	70	33	27	30	42	26	17
		L	52	57	72	55	36	27	5	..	..	..	..	1
July ..	T		2	3	4	4	3	10	2	2	3	10	4	
		L	3	5	7	7	5	2	..	..	..	..	..	..
Aug. ..	T		1	1	2	4	1	..	2	1	..	..	1	3
		L	2	3	5	3	2	..	..	..	..	..	..	..
Sept. ..	T		15	11	13	13	12	40	16	7	5	12	6	5
		L	23	28	30	28	20	14	4	..	..	..	..	..
Oct. ..	T		13	16	13	11	11	20	7	5	3	2	1	1
		L	32	35	37	32	27	20	1	..	..	..	..	..
Nov. ..	T		3	1	1	1	1	2	..	..	..	..	..	..
		L	14	14	9	9	6	4	1	..	..	..	..	..
Dec. ..	T		..	..	1	2	..	1	1	..	..	..	..	..
		L	4	5	5	2	3	..	..	..	..	..	..	..
Total ..	T		75	96	111	106	96	160	65	51	45	73	43	32
		L	159	180	203	171	129	92	16	0	0	1	0	1
Average per year.	T		1·2	1·5	1·7	1·6	1·5	*2·4*	1·0	0·8	0·7	1·1	0·7	0·5
		L	2·4	2·8	*3·1*	2·6	2·0	1·4	0·2	0·0	0·0	0·0	0·0	0·0

In *Fig. 2*, it will be observed that all the stations except Bombay, show sudden changes in the trend of the curves. In the case of Agra, for example, up to 1923 the number of thunderstorms reported is very small and in the next year the curve atonce shoots up, showing that some serious change in the system of observation itself must have occurred in 1924. As a matter of fact, in that year the Agra surface observatory was shifted from the town to the Upper Air Observatory and regular weather diaries began to be maintained there. Naturally therefore, under better supervision, reliable and systematic observations were started only after 1924. Similarly the distinct changes in the general trend of the curves for Calcutta and Madras are perhaps due to similar reasons. From this analysis therefore it appears that only the data of the years given in the third column of *Table III* can be considered as reliable.

As regards the secular variations no definite conclusions can be drawn as the different stations do not show any great similarity in their yearly march of electrical activity. Bombay, as mentioned before, does show some long period waxing and waning but the period is not definite. It neither shows any connection with the sun-spot cycle.

It is interesting to compare the seasonal variation of rainfall with that of thunder. The monthly averages of rainfall shown by the broken curves in *Fig. 3* are derived from the rainfall data at these stations extending over long periods. The two prominent maxima of thunder (*Fig. 3*) in April and October with a deep minimum in July-August at Trivandrum, gradually get less prominent as we move towards North India ; the intermediate minimum at the same time is filled up and finally all are merged into one maximum in July, as at Agra. A similar, but not identical, variation with latitude is also known to exist in the case of rainfall in India. The thunderstorm maximum and the rainfall maximum do not coincide. The thunderstorm activity is at its maximum when there is sufficient but not too much of moisture in the atmosphere ; and thus it either precedes or follows the rainfall maximum.

Among the places discussed, the total number of thunderstorm days in a year is greatest at Trivandrum, the average being 91 days per year. It is situated in one of the most thundery regions of the globe. It may be pointed out here, that in some years thunder and lightning are reported almost every day for a whole month. This large frequency is mainly due to the geographical position of Trivandrum[5], lying as it does, on the sea-coast in the paths of both the southwest and the northeast monsoons and close to the Western Ghats.

Agra represents a typical north Indian station, with only 40 days of thunder on the average per year.

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alone. The diurnal variation of the electrical activity at Bombay is shown in *Table I* and *Fig. 1*, and is typical of a coastal station on the west coast of the Peninsula of India. The curves of diurnal variation of lightning are not comparable with those of thunder as the number of occasions of lightning observed during day time is bound to be very small.

Thunder is an exceedlingly rare phenomenon at Bombay in the winter months, December, January and February. In 65 years, the number of days of electrical activity in December, January and February were 25, 12 and 19 respectively, as against 569 days in June and 459 days in October. There are two hours of maximum thunderstorm activity in the P. M. hours, one between 15 and 16 hrs. and the other between 21 and 22 hrs. There is also a marked subsidiary maximum in the early hours of the morning, particularly in June, September and October.

Another interesting feature shown by these figures of thunder and lightning is that while in all seasons the number of occasions when lightning alone was recorded during the dark hours is larger than those of thunder, the ratio of the former to the latter is much larger during the drier months, November to May (generally greater than 6 : 1) than during the monsoon months, June to October (2·3 : 1 to 1 : 1). This is apparently due to the fact that the formation of afternoon cumulus with feeble electrical activity, but without developing into full-fledged thunderstorms is much more common in the drier months than in the monsoon. The diurnal variation of thundery weather at Trivandrum[1] is somewhat similar to that observed at Bombay. Analysing the data collected at Trivandrum by Mr. J. A. Broun during the period 1855-64, Sir John Eliot[4] points out " the day maximum is at 4 P. M. in the hot season and at 3 P. M. in the remaining three seasons of the year and is, on the mean of the whole year, at 3 P. M. Thunderstorms are least frequent in the morning hours from 7 A. M. to 10 A. M..... There is a feeble secondary maximum from midnight to 5 A. M. It is somewhat variable in its occurrence in different seasons and is very feebly marked compared with the absolute maximum. The corresponding secondary minimum is at 11 P. M."

The year-to-year variation of the electrical activity at Bombay not considering the above distinction of thunder and lightning is shown in *Fig. 2* and *Table II*. The suggestion of the existence of a periodicity in the above curve encouraged a further examination of thunderstorm data at other places in India; and accordingly the data of the following four stations for which we have long records were examined :— Trivandrum, Madras, Calcutta and Agra. Detailed weather diaries, similar to those kept at Bombay were not available for these places, therefore the information was obtained from the Daily Weather Reports of the India Meteorological Department. *Table III* gives the years during which the reports of the different stations have been analysed.

TABLE III.

Station.	Period of thunder and lightning reports.	
	Whole Period.	Period selected.
Trivandrum	1890-1938	1900-1938
Madras	1879-1938	1906-1938
Bombay	1873-1937	1873-1937
Calcutta	1879-1938	1912-1938
Agra	1879-1938	1924-1938

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Frequency of thundery conditions at Bombay compared with those at some other stations in India.

BY

M. W. CHIPLONKAR.

(Received on 26th October 1940.)

Abstract.—Frequency distribution of thunderstorm activity at Bombay is studied over a period of 65 years, and an examination is made to see whether any regular long period variation exists in the frequencies of thunderstorms at Bombay and at a few other stations in India. At Bombay there are two hours of maximum thunderstorm activity in the P. M. hours, one between 15 and 16 and the other between 21 and 22 hrs. There is also a subsidiary maximum in the early hours of the morning, particularly in June, September and October. In all months, during the night hours, the number of occasions of lightning alone is greater than that of thunder and lightning, the ratio of the former to the latter being greater during the drier months November to May (generally more than 6 : 1) than during the wet months June to October (2. 3 : 1 to 1 : 1).

Comparing the seasonal variation of thunderstorm activity with that of rainfall at the same station, it is found that their maxima do not coincide, but the thunderstorm maximum either precedes or follows the rainfall maximum, depending upon the season. No definite conclusions could be drawn regarding the secular variation.

There have been a few studies of the frequencies of thunder and lightning in India. Analysing the data of Trivandrum for the period 1902—1914 Ramanathan[1] pointed out that the general meteorological conditions in the months of maximum and minimum frequencies of thunderstorms are the most and least favourable respectively, for their formation on Simpson's theory. Sohoni [2] made an analysis of the frequencies of thunderstorms at Calcutta using the autographic records obtained at that place during 1900—1926. Information on the frequencies of thunderstorms at a number of stations in India for the period 1914—1923 is collected in the Scientific Note No. 5 of the India Meteorological Department[3]. The present note contains a brief analysis of the main features of thunderstorm activity at Bombay followed by an examination as to whether any regular long period variation is detectable in the frequencies of thunderstorms at Bombay and at a few other places. The information about thundery conditions at Bombay was taken from the weather diaries which have been kept carefully at the Bombay observatory since 1873.

The information was first collected in separate monthly tables giving the distribution of electrical activity in hourly intervals of each day for all the 65 years,—distinguishing occasions of thunder or thunder and lightning from those of lightning

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INDIA METEOROLOGICAL DEPARTMENT

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The Sea-Breeze at Madras

BY

A. K. ROY.

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The Sea-Breeze at Madras.

BY

A. K. Roy.

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Abstract.—The paper contains a preliminary study of the sea-breeze at Madras, a station situated on the east coast of the Indian Peninsula. It is found that sea-breeze from the east, which is often very well marked, sets in in the afternoon or evening with some of the characteristics of a cold front during the monsoon months June to September, even though the prevailing gradient wind from the west is itself of oceanic origin but heated by passage over land. Some statistical data relating to the sea-breeze are given in part I of the paper, while part II contains some suggestions regarding the estimated depth of the sea-breeze and the time of its onset, based on the study of the easterly components of the wind at lower levels at dawn and 1400 hrs.

Introduction.

A study of the sea-breeze at Poona and Karachi, two stations situated on or near the west coast of the Indian Peninsula is contained in earlier papers[1] of this series by K. R. Ramanathan and L. A. Ramdas. The phenomenon of sea-breeze is most marked at stations on the west coast during the period October to May, when the prevailing wind at lower levels is off shore, the wind blowing mainly from some northeasterly direction. At stations such as Madras, on the other hand, which are situated on the east coast, the wind during the greater part of the above season is usually between northeast and southeast and, as such, there is a permanent or more or less continuous sea-breeze except for a few hours of the night or the early morning. During the period mid-May to mid-October, the prevailing wind over the Peninsula is from the west, and it is during this season that the effect of the sea-breeze, if any, at a station on the east coast would reveal itself conspicuously by a sudden reversal of the wind direction from west to east. As, however, the westerly to southwesterly winds blowing across the Peninsula during June to September also bring in air of oceanic origin, which is moist and cool, it was of interest to find out whether the effect of insolation at a station on the east coast would be sufficient to cause this air to be replaced by the fresh sea-breeze from the east and if so, whether the phenomenon in such cases would be attended by the same characteristics of a sudden fall of temperature and rise of humidity as are noticed when the land air at a west coast station gives way to the sea-breeze. The anemograph, thermograph and hygrograph charts of Madras for the two years February, 1938 to January, 1940 were accordingly examined, and these showed that sea-breeze, which is at times well pronounced, sets in at the station in the afternoon or evening on quite a large number of days during the mid-monsoon season also. Some statistical data relating to the sea-breeze at Madras, collected as a result of the above study, are included in Part I of the paper. A comparison of the easterly components of the wind at lower levels at dawn and at 1400 hrs. gives some useful information regarding the depth of the sea-breeze at Madras and the time of its onset, and this is mentioned in Part II of the paper.

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[1] **Scientific Notes Vol. III, No. 30, by K. R. Ramanathan.**
Scientific Notes Vol. IV, No. 41, by L. A. Ramdas.

PART I.

Location of the Madras Observatory and the position of the P. T. anemometer.—Madras city (Lat. 13° 4′N, Long. 80° 15′E.) is situated on the Coromandel Coast, about midway between Point Calimere and Masulipatam, the coast line near Madras running almost due north to south. The surrounding country is practically flat, the nearest hills being 50 miles to the northwest. The observatory (22 ft. above sea level) is situated in Numgembaukam, one of the suburbs of the city at a distance of two miles from the sea. Besides being a first class meteorological observatory with full complement of self-recording instruments, it is a pilot balloon station making two flights a day, one at dawn and the other at about 14 hrs. A Dines Pressure Tube anemometer recording both direction and velocity of the wind is maintained at the observatory with its head at a height of 55 ft. above ground.

General characteristics of the sea-breeze at Madras.—As has been mentioned already, the gradient wind at Madras during the winter months, November to April, being usually from the east, a more or less permanent sea breeze prevails at the station during this season. The effect of the land breeze, which is caused by radiational cooling of the ground at night, introduces a component of wind from the west, and causes the direction of the wind to turn to north or northwest from about midnight to the early hours of the morning, after which the wind veers again to northeast or east. The change-over from the land-breeze to the gradient onshore wind takes place rather gradually, and partly for this reason and partly for the fact that this occurs quite early in the day before the insolational heating of the ground produces any appreciable temperature gradient between the land and the sea, the transition as above is not accompanied by any noticeable fall of temperature or rise in humidity as is found to occur during the advance of a well marked sea-breeze front. During the period June to September, however, and also on some days in May and October when the prevailing wind at the station is from land to sea, a sudden onset of the sea-breeze from the east in the afternoon, often causes a sharp fall of temperature, a rise of humidity and a marked shift in the wind direction. *Table I* below shows the average number of days of occurrence of sea-breeze at Madras in the different months of the year.

TABLE I.

(Based on data of two years February, 1938 to January, 1940).

Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
Daily or Continuous.	Daily or Continuous.	Daily or Continuous.	Daily or Continuous.	Daily or Continuous.	27	25	21	24	27	29	29

During the period, November to April, the sea-breeze at Madras is either more or less continuous or occurs early in the morning usually before 10 hrs. I.S.T. With the progress of the hot and monsoon season, the westerly component of the wind over the region strengthens gradually, and the growth of the sea-breeze is often retarded to late hours of the afternoon or evening. The average number of occasions on which the sea-breeze sets in at different hours of the day during the months May to October are shown in *Table II.*

TABLE II.

Average number of occasions of the setting in of the sea-breeze at different hours of the day, and monthly mean velocity of resultant wind at 1 km above sea level (February, 1938 to January, 1940).

Hours. / Months.	Before 1100 hrs.	1100 — 1159	1200 — 1259	1300— 1359	1400 — 1459	1500 — 1559	1600— 1659	1700— 1759	1800 hrs. to later.	Mean velocity of wind at dawn at 1 kmA.S.L. (m.p.s.)
May ..	2	8	9·5	6	2	1·5	0	1	0	4·1
June ..	1	1	2	5·5	7	5·5	1·5	1·5	2	11·4
July ..	0	0	2·5	3·5	5	4·5	4·0	2·5	2·5	12·4
August ..	1	3	3·5	4·5	3·5	1	3·5	1·5	0·5	10·8
September ..	1	2	3	5·5	4	2·5	4	1	1	6·6
October ..	6	5	8·5	1·5	2·5	1	1	0	1	1·4

In the last column of the table is shown the monthly mean velocity of the resultant wind (nearly westerly) at 1 km above sea level at Madras. It is seen that as this velocity increases and reaches a maximum in July, the hour of occurrence of the sea-breeze gets retarded, and as the velocity decreases again the time is gradually advanced until in October the sea-breeze occurs on most days before 1300 hrs.

Temperature changes associated with sea-breeze.—As has been mentioned already, the arrival of a sea-breeze front at Madras is often accompanied by a sudden fall of temperature, the fall of temperature being usually more marked, the nearer the time of its occurrence to the epoch of maximum temperature. An analysis was made of this drop of temperature in 15 minutes with the onset of the sea-breeze on different occasions during the months May to October, and the results of the analysis are given in the table below.

TABLE III.

Average number of occasions of temperature fall of different order. (February, 1938 to January 1940).

Temperature fall / Month.	<1·0°F.	1·0–1·9	2·0–2·9	3·0–3·9	4·0–4·9	5·0–5·9	6·0–6·9	7·0 or more.
May	4	4·5	5	5·5	4·5	2	3	2
June	2	3·5	2·5	4·5	2·5	2·5	4	3
July	2	2·5	9	2	4	3·5	1	0·5
August	5	6·5	3	2	2	0	0·5	2·5
September	3	8	6	4	1	1	0·5	0
October	11·5	9	0·5	2	0	0	0	0

The advent of the sea-breeze is also accompanied by a sudden increase in relative humidity, the magnitude of the rise depending on the difference between the temperature and the moisture content of the air that was present at the station originally and of the fresh sea-breeze which replaces it. The frequencies of humidity changes of different order as were found to be associated with the sea breeze on different occasions during the period under examination are shown in the table below.

TABLE IV.

Average number of occasions of humidity rise of different order. (February, 1938 to January, 1940).

Increase in R.H. / Month.	Less than 5%.	5 to 9%.	10 to 14%.	15 to 19%.	20 to 24%.	25 to 29%.	30% or more.
May ..	2·5	4·0	9·0	7·0	4·0	3·5	0·5
June ..	3·0	4·5	2·0	7·0	5·5	3·0	0·5
July ..	1·5	4·0	3·5	4·5	8·5	2·5	0·5
August ..	1·5	7·5	5·5	3·5	1·0	0·5	2·0
September ..	1·5	5·5	7·0	6·0	3·5	1·0	0
October ..	0·5	6·0	7·5	2·0	1·0	0	0

It is seen that well marked sea-breeze occurs frequently at Madras during the period May to October, and that even on days of strong monsoon when fresh westerly to southwesterly winds from the Arabian Sea blow over the station, the difference in solar heating of the coastal region and of the neighbouring water surface during the day causes this local wind current to set in with some of the characteristics of a cold front.

PART II.

Estimated depth of the sea-breeze at Madras.—*Table V* below gives the difference between the mean easterly component of morning and afternoon winds in different months at Madras at surface, 0·5, 1, 1·5 and 2 km above sea level, based on available pilot balloon observations at dawn and 1400 hrs. I.S.T.

TABLE V.

Difference between the mean easterly component of morning (Em.) and afternoon (Ea.) winds, i.e., *(Ea-Em) at Madras at different heights. (Based on data of eight years 1932-39).*

Month. \ Heights.	Surface.	0·5 km.	1·0 km.	1·5 km.	2·0 km.
January	+1·8	—0·6	—1·3	—1·8	—2·0
February	+2·1	+0·5	—1·8	—1·0	—0·7
March	+2·0	+0·9	—1·1	—0·9	—0·4
April	+2·1	+2·7	—0·6	—1·0	—0·6
May	+2·0	+6·7	+1·3	—0·9	—1·5
June	+0·7	+8·2	+4·0	+1·3	—1·4
July	—0·3	+6·2	+4·3	+2·7	—0·9
August	+0·1	+6·1	+3·0	+1·5	—0·4
September	+0·8	+5·3	+2·2	+0·4	—1·3
October	+1·2	+2·5	0	—1·1	—1·9
November	+1·3	—0·1	—1·3	—1·4	—1·1
December	+1·7	—0·6	—1·4	—1·9	—1·6

The annual variation of the above difference (Ea-Em) is shown diagrammatically in *Fig. 1.* A smooth curve, AA′ has been drawn on the diagram indicating the height up to which Ea-Em has a positive value in different months. It is seen that the easterly component of the wind at lower levels increases from morning to afternoon, and the height up to which the strengthening of this component takes place is a minimum in winter and increases gradually to a maximum in July and August. This gain in the easterly component of wind is apparently caused by the differential heating of the land area and the surrounding seas by insolation during the day and the consequent superimposition of a thermal low over the general pressure field over land, and is also partly due to the effect of the local sea-breeze on those days when this has already set in by 1400 hrs.

In order to separate out the effect of the local sea-breeze from the more general effect arising out of the land and sea distribution, the mean difference (Ea-Em) has been calculated separately for (*a*) all days, (*b*) days on which sea-breeze started before 1400 hrs. and (*c*) other days, during the months May to October, the average being taken over the two years 1938 and 1939 for which sea-breeze data are available. The mean values of (Ea-Em) for the three different classes of days are plotted in *Fig 2* against the respective months' and heights. The three curves AA′, BB′ and CC′ show respectively the heights up to which mean (Ea-Em) has a positive value, that is, the heights up to which the easterly component of wind strengthens from dawn to afternoon, on days coming under the three classes (*a*), (*b*) and (*c*). Data for the period, May to October, only have been analysed, as the sea-breeze during the remaining months is either continuous or sets in long before 1400 hrs. A comparison of the three curves in *Fig. 2* shows that the increase in the easterly component from morning to afternoon occurs up to a greater height on days on which the onset of the sea-breeze is delayed beyond 1400 hrs. than on days when the breeze has already set in by that time. This feature is brought out more clearly in *Fig. 3* in which the values of (Ea-Em) on these two classes of days in July and August have been plotted against corresponding heights. Curves (*b*) relate to days on which sea-breeze started earlier than 1400 hrs. and curves (*c*) to late or non-sea-breeze days. The difference in the values of (Ea-Em) between the two classes of days, which gives a measure of the mean contribution, by the sea-breeze front, of easterly component of wind at various levels is shown by the curves (*d*). *Figs. 2* and *3* make it clear that, as a result of the sea-breeze, a decrease in the easterly component occurs above a certain level and this marks the upper limit of the sea-breeze layer or the lower limit of the " return current ", a well-known phenomenon associated with the sea-breeze. At heights lower than the above, the additional easterly component which is superposed by 1400 hrs., is obviously greater on days of class (*b*) than of class (*c*). The difference between the values of mean (Ea-Em) at various heights on these two classes of days has been plotted in *Fig. 4*, and a line SS drawn through the points of zero difference. The line so drawn gives the mean height to which the effect of the sea-breeze extends, that is, the mean thickness of the breeze at 14 hrs. in the different months May to October. It is seen that, on the mean, the sea-breeze is about 0·5 km deep in May and that the depth increases to about 1 km in September, decreasing again to about half the value in October. It may be noted that the depth of the sea-breeze, as determined above, does not give the height of the layer in which the wind becomes actually easterly, but merely indicates the height up to which the easterly component of the wind is augmented by the contribution from the sea-breeze front.

Time of incidence of the sea-breeze and its dependence on the strength of the westerly component of wind at higher levels.—The following table gives the mean westerly component of wind at Madras at dawn at 0·5, 1, 1·5 and 2 km above sea level on days of two different classes, according as the sea-breeze starts earlier or later than 1400 hrs. The mean values for days of the former class are shown in column A and those of the latter in column B. The figure within brackets under column A gives the percentage of cases in which the sea-breeze started later than 1400 hrs. even though the westerly component of wind at dawn was less than the mean value shown in that column. A similar figure under column B gives the percentage of occasions on which the sea-breeze started earlier than 1400 hrs. inspite of the fact that the westerly component at dawn was greater than the mean value shown.

TABLE VI.

Mean westerly component of wind at dawn on days of classes A. and B.

Month.	0·5 km.		1 km.		1·5 km.		2 km.	
	A.	B.	A.	B.	A.	B.	A.	B.
May	+9·6(*Nil*)	+14·9(7)	+6·5(*Nil*)	+11·3(7)	+2·7(20)	+8·2(4)	+0·5(*Nil*)	+5·7(5)
June	+10·5(9)	+13·9(12)	+9·3(6)	+14·3(8)	+7·1(14)	+12·1(8)	+5·1(14)	+10·3(8)
July	+9·8(22)	+12·3(5)	+7·7(7)	+13·3(6)	+7·3(7)	+14·1(6)	+6·1(7)	+13·3(6)
August ..	+6·9(3)	+12·3(4)	+6·2(3)	+13·1(4)	+3·9(*Nil*)	+12·8(*Nil*)	+2·4(3)	+12·1(*Nil*)
September ..	+6·6(39)	+7·9(26)	+5·1(28)	+6·8(20)	+3·7(34)	+5·5(25)	+3·1(19)	+5·5(20)
October ..	+1·1(8)	+7·3(8)	—0·7(*Nil*)	+7·9(*Nil*)	—0·3(*Nil*)	+5·9(*Nil*)	+0·3(*Nil*)	+5·6(*Nil*)

It will be seen from the above table that the strength of the westerly component of wind at dawn at higher levels gives a good indication of early or late onset of the sea-breeze, and that forecasts in this respect should prove correct in most cases when the value of the westerly component in the morning is either less than the limits indicated in column A or greater than that shown in column B.

In *Figs. 5 and 6* are shown the anemograph, thermograph and hygrograph records at Madras for the 21st and 25th July, 1939 in illustration of the effects of the sea-breeze which set in at the station on the two dates at 1650 and 1235 hrs. I.S.T. respectively. The sea-breeze on the 21st was brought in with a sudden shift in the wind direction from northnorthwest to southeast, and this was accompanied by a fall of temperature of about 5·5°F in 15 minutes and a rise of humidity by about 25 per cent. On the 25th when the sea-breeze occurred earlier in the day, there was a fall of temperature of about 3·5°F and a rise of humidity by 9 per cent., with a shift in the wind direction from northwest to eastsoutheast, through north. The westerly component of the wind at 2 km at dawn on the 21st, the day of late onset of the sea-breeze, was 16·7 m.p.s. while that on the 25th was 5·4 m.p.s. only.

In *Table VII* below are given the mean winds at various levels at Madras in morning and afternoon on days on which sea-breeze started earlier than 1400 hrs.

TABLE VII.

Mean Winds at Madras in morning and afternoon on days of early Sea-breeze during the months May to October.

Month.	Height.	Mean wind (Dawn).		Mean wind (1400 hrs.).		Month.	Height.	Mean wind (Dawn).		Mean wind (1400 hrs.).	
		Dir.	Vel. m.p.s.	Dir.	Vel. m.p.s.			Dir.	Vel. m.p.s.	Dir.	Vel. m.p.s.
May	Surface	213	1·3	142	2·9	August ..	Surface	243	0·7	120	2·2
	0·5 km.	250	9·8	225	1·0		0·5 km.	263	7·0	229	0·9
	1·0 „	265	5·9	286	3·7		1·0 „	284	6·4	287	3·0
	1·5 „	294	3·0	311	4·1		1·5 „	298	4·4	291	4·2
	2·0 „	350	2·9	328	3·6		2·0 „	306	2·9	291	4·2
June	Surface	248	1·6	130	3·0	September	Surface	225	0·9	129	1·9
	0·5 km.	273	11·0	206	1·0		0·5km.	246	7·2	235	1·2
	1·0 „	284	9·6	306	6·3		1·0 „	268	5·1	278	3·8
	1·5 „	289	7·6	275	6·5		1·5 „	297	4·2	286	5·3
	2·0 „	289	5·4	275	7·0		2·0 „	303	3·7	287	4·9
July	Surface	251	1·2	106	2·2	October ..	Surface	346	0·4	102	1·5
	0·5km.	275	9·8	214	1·1		0·5 km.	218	1·8	62	2·4
	1·0 „	287	8·1	274	5·5		1·0 „	60	0·8	21	1·9
	1·5 „	296	8·1	275	7·1		1·5 „	12	1·4	340	2·0
	2·0 „	290	6·5	273	7·5		2·0 „	353	2·4	333	2·5

Structure of the sea-breeze at Madras.—With a view to obtain an approximate idea of the structure of the sea-breeze at Madras, a few special pilot balloon flights were arranged at the station on three days during the monsoon season of 1940. Unfortunately, on the first two days, the sea-breeze was either very short-lived or occurred too late in the evening, and, as such, no data representing conditions after the sea-breeze could be obtained. Later, with the help of the criterion, as mentioned above, for an early advance of the sea-breeze, it was possible to fix, for such special flights, a day on which the sea-breeze would start earlier than 1400 hrs. The next set of flights were therefore arranged on 1st September on which the sea-breeze, according to the above criterion, was expected to set in before 1400 hrs.; the sea-breeze on this day actually commenced at 1220 hrs. The trajectories of the six flights made between 1100 and 1335 hrs., together with a table giving the easterly components of winds at various heights are included in *Fig. 7 (a)*. The negative sign of the easterly components shows that the wind at all heights at 1100 hrs. was from the west. This was so at 1200 hrs. also, but it is seen that the westerly component of the wind at the lowest levels had decreased considerably in the mean time. For instance, at 0·2 km, the value of the westerly component dropped from 6 to 1 m.p.s. only, indicating that during the interval in question an easterly wind of 5 m.p.s. was superposed on the westerly wind which prevailed at 1100 hrs. It would seem that the sea-breeze had already made its appearance near about the ground level, although it was not yet on with its full vigour to obliterate completely the effect of the prevailing wind from the opposite direction. The anemograph chart of the day shows that at 1130 hrs. the wind veered from northwest to northeast but changed again to westnorthwest or northwest after a few minutes, showing that a struggle between the prevailing westerly wind and the advancing sea-breeze from the east had begun as early as 1130 hrs., although the latter was not able to establish itself fully till about 1220 hrs.

Now if we make the assumption that during the interval between 1100 and 1335 hrs. I.S.T. the winds at the lower levels would have remained more or less the same but for the incidence of the sea-breeze, the difference between the easterly component of wind at any particular level at 1100 hrs. and that at the same level at any subsequent hour should give a measure of the contribution of the sea-breeze by that hour. These differences at various heights up to 2 km at the different hours of special pilot balloon flights have been plotted in *Fig. 7 (b)* and the points corresponding to the heights of zero difference jointed by a smooth line. The diagram so obtained gives an idea of the structure of the sea-breeze on 1st September, 1940, and shows that the maximum depth of the sea-breeze on this day was about 0·85 km.

M2DGofOb—425—28-8-41—GIPS

Plate I

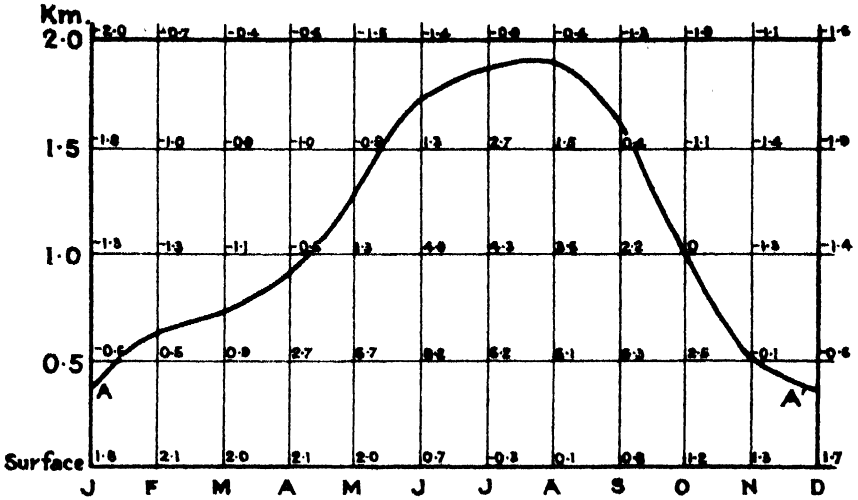


Fig. 1. Annual variation of the difference (Ea—Em) between the mean Easterly component of wind in morning and afternoon at various levels above Madras.

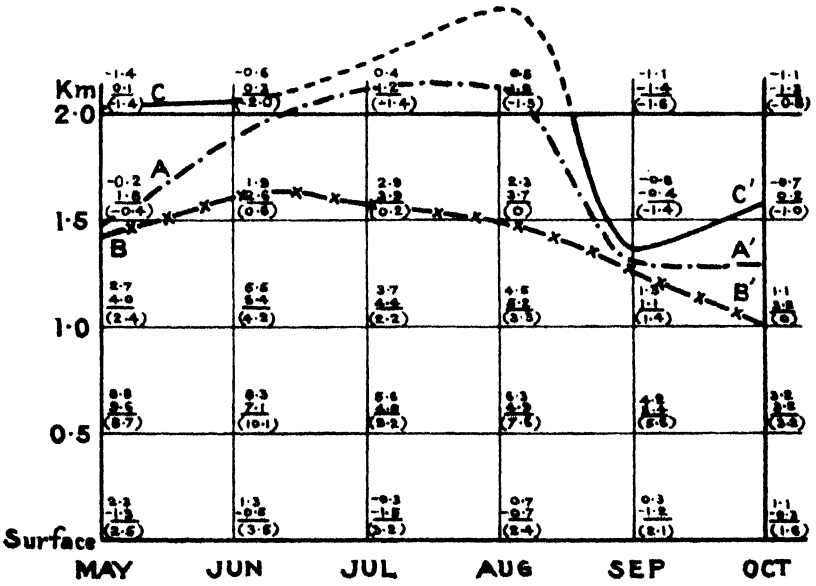
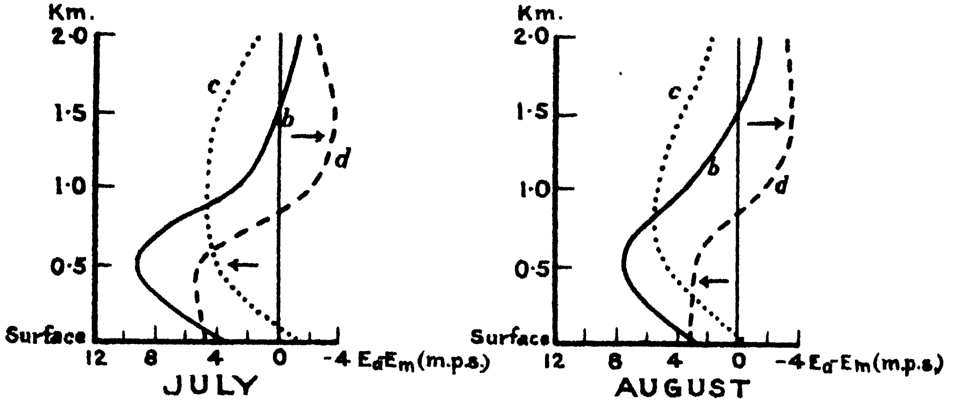


Fig. 2. Curves showing the heights upto which Easterly component of wind at 1400 hrs. is greater than that in the morning during the months May to October.

Figures in top row give mean (Ea-Em) for all days.	AA'	-	Based on mean of all days
Figures underlined give mean (Ea-Em) for all days on which sea-breeze started after 1400 hrs.	BB'	-	Based on mean of days on which sea-breeze started before 1400 hrs.
Figures within brackets give mean (Ea-Em) for days on which sea-breeze started before 1400 hrs.	CC'	—	Based on mean of days on which sea-breeze started after 1400 hrs.

G. P. I. O. POONA, 1941.

Plate II



JULY AUGUST

Fig. 3. (Ea-Em) at different levels upto 2 km.
b — days on which sea-breeze started before 1400 hrs.
c ··· ,, ,, ,, ,, ,, after ,, ,,
d - - difference between b and c.

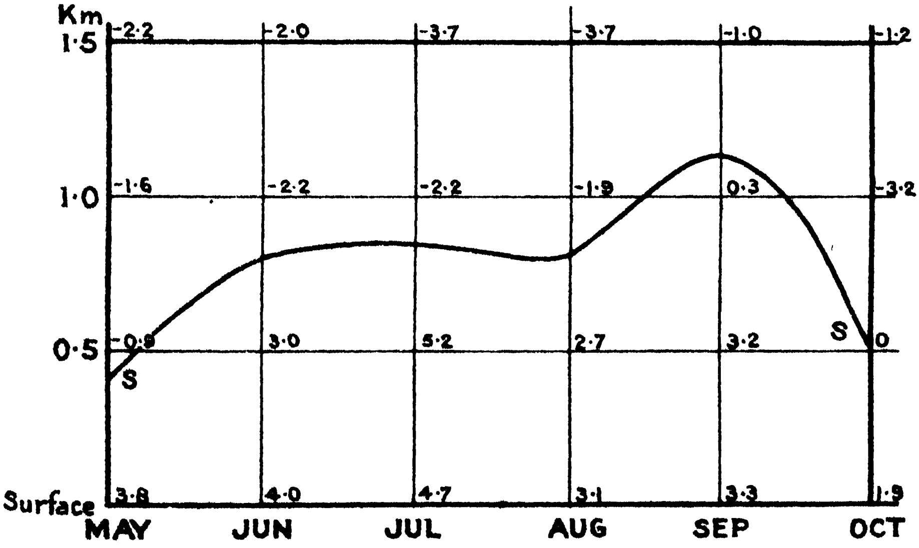


Fig. 4. Curve showing the height upto which the sea-breeze extends at 1400 hrs.

G. P. X. O. POONA. 1941.

Plate III

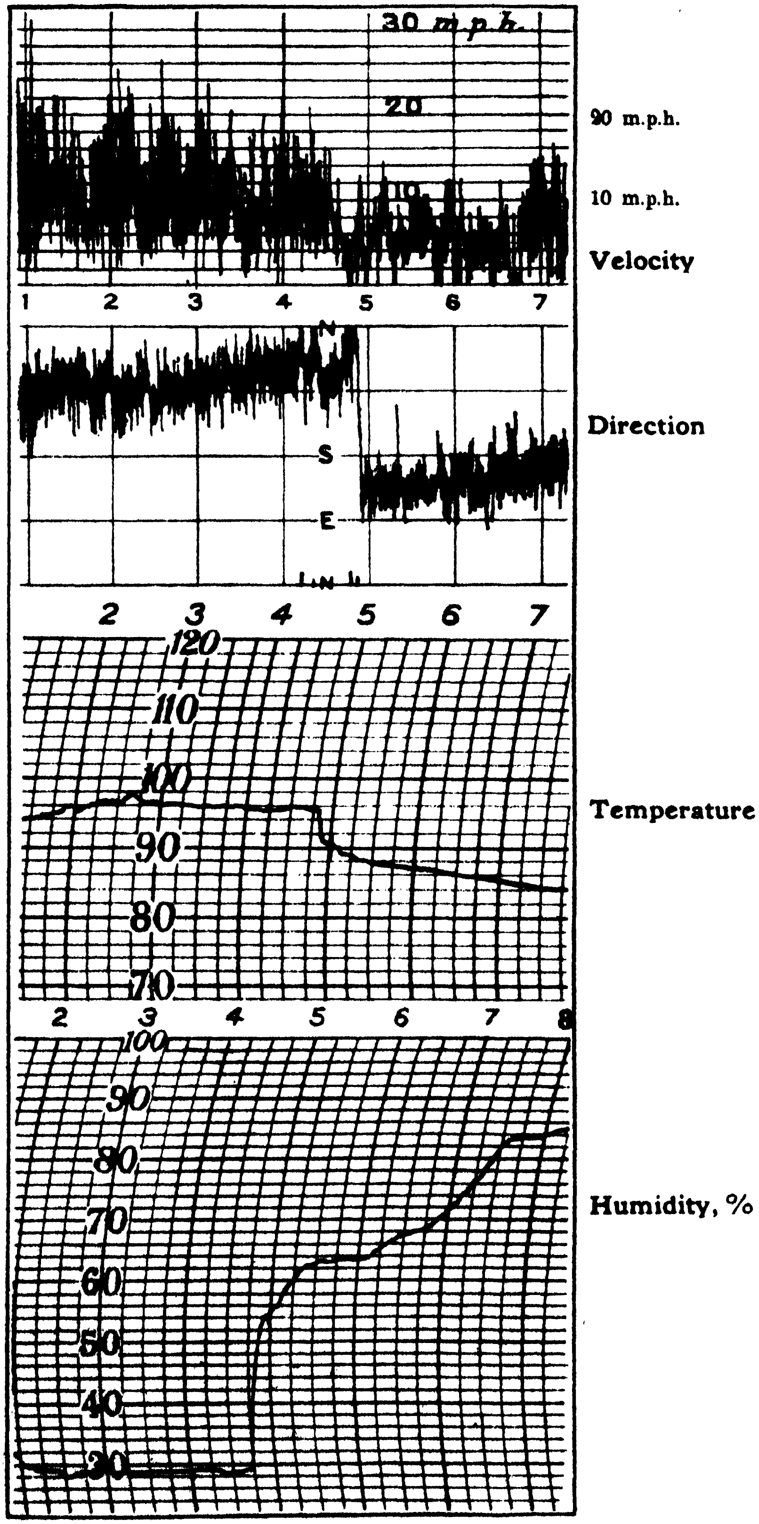


Fig. 5. Wind, temperature and humidity at Madras on 21-7-1939

Plate IV

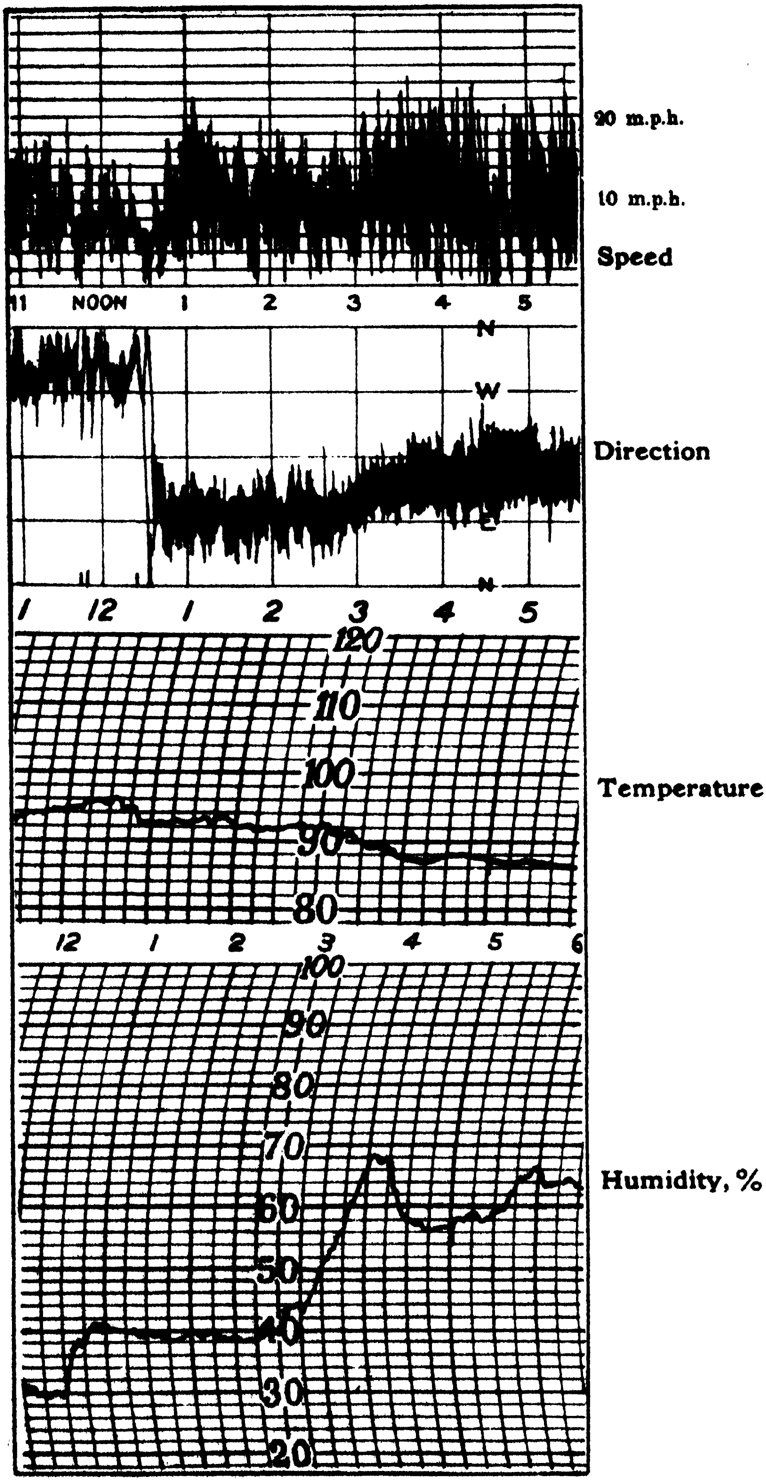
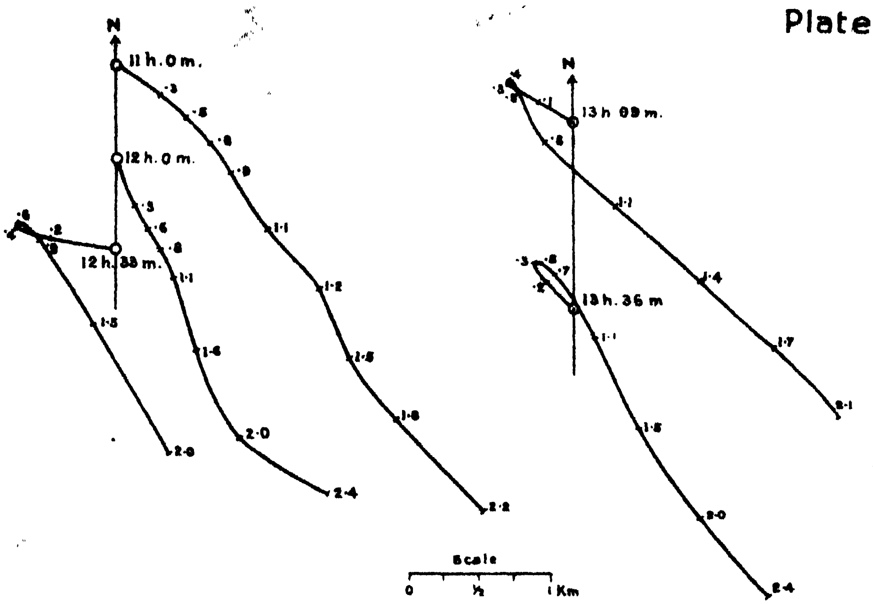


Fig. 6. Wind, temperature and humidity at Madras on 25-7-1939

Plate V



11 h. 0 m.		12 h. 0 m.		12 h. 33 m.		13 h. 09 m.		13 h. 36 m.	
Km.	V_g (m/s)	Km.	V_g (m/s)	Km.	V_g (m/s)	Km.	V_g (m/s)	Km.	V_g (m/s)
Surface	−1·3	Surface	−1·0	Surface	1·8	Surface	1·3	Surface	1·9
0·2	−6·0	0·2	−1·0	0·2	5·1	0·2	3·1	0·2	2·8
0·5	−2·2	0·5	−2·7	0·5	0·2	0·5	−0·7	0·5	−1·4
1·0	−1·9	1·0	−1·2	1·0	−2·7	1·0	−4·5	1·0	−2·5
1·5	−2·1	1·5	−1·4	1·5	−3·9	1·5	−4·7	1·5	−3·0
2·0	−4·6	2·0	−4·0	2·0	−4·8	2·0	−3·9	2·0	−3·9

Fig. 7 (a) Trajectories of special pilot balloons sent up between 1100 and 1336 hrs. on 1-9-40, and tables giving Easterly components of winds upto 2 km

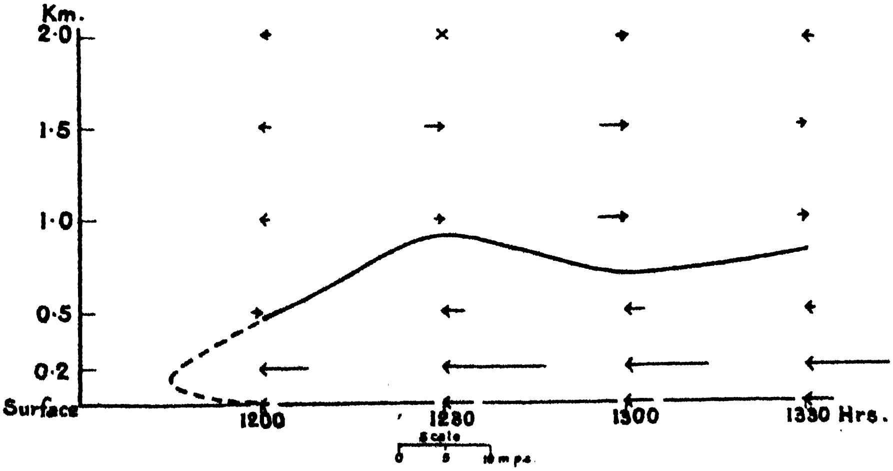


Fig. 7 (b). Additional Easterly or Westerly component of wind superposed during the interval between 1100 hrs. and the hour of successive pilot balloon flights between 1200 hrs. and 1336 hrs.

G. P. M. O. POONA, 1941.

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BY

V. Doraiswamy Iyer.

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Forecasting the 'Northeast monsoon' rainfall of South Madras

BY

V. DORAISWAMY IYER.

(Received on 2nd December 1940.)

Abstract.—The paper investigates the possibility of evolving a forecasting formula for the 'northeast monsoon' rains of South Madras (Southeast Madras + Malabar) from previous weather conditions. A selection of likely factors is made and three regression formulæ are evolved. A formula based on (1) South American pressure from June to August, (2) Bangalore westerly upper winds from 3 to 5 km. in September and (3) Agra westerly upper winds from 5 to 8 km. in September, is found to give a significant multiple correlation coefficient of 0·60. A formula based on the same factors gives similar results when applied to Southeast Madras alone.

Introduction.

In a country like India, which has a well marked monsoon rainfall on which the agricultural prosperity of the country depends, it is but natural that attempts should be made to form some estimate of the coming season's rainfall. Soon after the formation of the India Meteorological Department, attention was directed to this question and the first forecast of the rainfall of the summer monsoon was issued in 1886. A forecast for the latter half of the monsoon season and another for the winter rains of northwest India were also added to this within the next decade. These forecasts have continued ever since ; they were placed on an objective statistical basis by Sir Gilbert Walker in 1909.

There is one region of India which is agriculturally important, *viz.*, southeast of the Peninsula, which receives comparatively little rain in the main monsoon months, June to September, but gets its chief rainfall in the months, October to December, when the southwest monsoon is retreating from the Indian area. This rainfall is popularly known as the 'northeast monsoon' rains, on account of the fact that the rain bearing winds blow from a northeasterly direction on the Coromandel Coast after passing round the seasonal low pressure area in the south of the Bay. An attempt is made in this paper to derive a forecasting formula for the 'northeast monsoon' rains of this region.

Inter-relation of the 'northeast monsoon' rainfall of the sub-divisions of Madras.

The 'northeast monsoon' rainfall of the retreating monsoon period is received not only in the southeast of the Peninsula which forms the meteorological sub-division of Southeast Madras, but also by the other sub-divisions of the province of Madras, *viz.*, Malabar, the Madras Deccan and North Madras Coast. In order to examine how the rainfall of Southeast Madras is related to those of the other sub-divisions in this season, the correlation co-efficients of the October to December rainfall of the four sub-divisions of Madras were worked out and are given in *Table I.*

TABLE I.

	Malabar.	Madras Deccan.	Madras Coast North.
Madras Southeast	+·61	+·34	+·18
Malabar	..	+·42	+·23
Madras Deccan	..	..	+·64

Adopting the 5 per cent. level of significance for the highest C.C. in a set of six C.Cs.(¹) any co-efficient above ·34 may be considered significant. It is seen that Malabar is highly correlated with Southeast Madras. The other two sub-divisions are poorly correlated with Southeast Madras although highly correlated between themselves. It was accordingly decided to combine Southeast Madras and Malabar; the combined region may be termed 'South Madras'. It may be mentioned that although Malabar receives its chief rains in the monsoon months, June to September, it has a secondary maximum of rainfall in October and records a fifth of the annual rainfall in the last three months of the year (*vide Fig. I.*). The normal rainfalls for the period October to December and their standard deviations for Southeast Madras, Malabar and South Madras based upon the data of the years 1875 to 1938, are given below.

	Normal rainfall.	Standard Deviation.
Malabar	20·12	4·7
Southeast Madras	17·97	6·0
South Madras	18·51	5·3

Relationship of 'northeast monsoon' rainfall with conditions in other parts of the world.

The correlation co-efficients of South Madras rainfall October to December, were then worked out with the pressures of several centres used by Walker in his investigations and with Dutch Harbour temperature (²). The C.Cs. for the preceding quarters, March to May and June to August, and for the partly contemporary quarter September to November are given in the following table.

TABLE II.

Correlation Co-efficients of South Madras rainfall, October to December, with various Centres.

	No. of years.	Two quarters before (March to May).	One quarter before (June to August).	Contemporary quarter (September to November).
Pressure—				
1. Northwest India	64	+·19	+·15	+·32
2. Seychelles	45	+·10	—·04	—·22
3. Mauritius	64	+·08	—·04	—·09
4. Batavia	64	+·26	+·20	+·30
5. Port Darwin	57	+·07	+·24	+·29
6. S. E. Australia	63	+·15	+·13	+·32
7. Manila	57	+·13	—·20	+·33
8. Tokio	53	—·16	—·09	+·25
9. Honolulu	52	—·17	—·31	—·12
10. Samoa	46	—·15	—·43	—·06
11. S. America	64	—·17	—·40	—·06
12. San Francisco	61	—·16	+·04	—·17
13. Vienna	59	—·06	+·10	—·10
14. Central Siberia	58	—·12	+·18	—·08
15. Tashkent	55	—·11	—·04	+·09
Temperature—				
16. Dutch Harbour	57	+·16	—·20	+·18

The number of years of data on which the C.Cs. are based vary from 45 to 64. Considering a series of sixteen co-efficients for any quarter, the value of the highest co-efficient that can occur due to the 95 per cent. random chance varies from 0·38 for 64 years' data to 0·45 for 45 years' data. Judging from this level of significance, it is found that the only C.Cs. that are of importance in the table are those of south Madras rainfall with South American pressure and Samoa pressure in the quarter June to August. If we adopt a more liberal level of significance, namely, 50 per cent. random chance, the highest coefficient that can be accepted varies from 0·26 to 0·31. By this criterion we may consider as significant the C.C. with Honolulu, June to August, and several C.Cs. in the quarter September to November mostly in the region to the southeast of India.

In the case of some of these pressure centres the C.Cs. for the month of September alone were worked out; they are: —Batavia +·32, Port Darwin +·25, Manila +·03 and S. America —·10. Other co-efficients which were worked out are given below :—

TABLE III.

	Number of years.	C.C. with South Madras rainfall October to December.
Pressure gradient Calcutta-Hyderabad, September	47	—·23
Pressure gradient Port Blair-Madras, September	60	+·04
Southern Oscillation, June to August	38	—·22
Sunspot numbers, previous year	63	+·05
Seychelles wind velocity, September	44	—·09
Seychelles wind velocity, October	44	—·16
South Rhodesian rainfall October to April	39	+·04
Java rain October to February	59	+·04
Peninsula rain, June to September	64	—·10
Northwest India rain, June to September	64	—·30
Upper Siam (Thailand) rain June to September	30	—·48
Saigon rain, June to September	29	—·28

Relationship with Indian upper winds.

Correlation co-efficients of South Madras rainfall with upper winds in the month of *September* at different heights over Agra, Bombay, Bangalore and Port Blair were worked out and are given in *Table IV*.

TABLE IV.

Correlation Co-efficients with Velocities of Upper winds in the month of September.

	No. of years.	Hts. in Km. above M. S. L.						
		2	3	4	5	6	7	8
Agra westerly component.	25	+·28	—·01	+·03	+·24	+·24	+·38	+·19
Bombay westerly component.	17	+·03	—·08	+·08	..	..	..	..
Bangalore westerly component.	24	+·02	—·32	—·38	—·27	—·21	..	..
Port Blair westerly component.	12	—·10	—·26	—·07	..	..	..	..

The winds in the layer 5 to 7 kms. over Agra give a C.C. of +·31. With the winds at levels 5 to 8 kms., which have been used for the winter forecast, the C.Cs. are (1) September +·29, (2) September II half +·25, and (3) September II half plus October I half +·41. The winds over Bangalore at levels 3 to 5 kms. give a C.C. of −·38, while with winds at each of the levels 3 and 4 kms. the C.C. is ·40. The Upper winds over Bangalore in the earlier months have no relation with South Madras rainfall.

Selection of factors and final regression formulæ.

An examination of the preceding relationships indicates that the following factors may be used for forming a regression equation for forecasting.

Factor.	C.C. with S. Madras rain.
1. South American pressure, June to August	−·40
2. Samoa pressure, June to August	−·43
3. Upper Siam rainfall, June to September	−·48
4. Northwest India rainfall, June to September	−·30
5. Agra westerly upper winds, 5 to 8 kms. September	+·29
6. Bangalore westerly upper winds, 3 to 5 kms., September	−·38

Of the above, the first two relate to areas lying on either side of the South Pacific High and have a C.C. of +·50 with each other. South American pressure has stood the test of time as a forecasting factor of importance for Indian rainfall, and is to be preferred to Samoa pressure.

Similarly the monsoon rainfall of Upper Siam and of Northwest India are highly correlated, the C.C. between them being +·73. Upper Siam is to be preferred on account of its higher C.C.

Using therefore S. American pressure, Upper Siam rainfall and the upper winds over Bangalore and Agra we form the following table of co-efficients.

	S. America pressure June to August	Bangalore westerly upper winds 3 to 5 kms., September.	Agra westerly upper winds 5 to 8 kms. September.	Upper Siam rainfall June to September.
South Madras rainfall October to December.	−·40	−·38	+·29	−·48
South America pressure ..	..	−·05	−·13	+·36
Bangalore winds	..	..	−·08	+·07
Agra winds	..	..	..	−·48

This gives the regression equation.—

[South Madras rain] = —·30 [S. America pressure]
—·37 [Bangalore winds]
+·07 [Agra winds]
—·31 [Upper Siam rainfall]

with a multiple correlation co-efficient R = ·65 .. .. .. (I)

Upper Siam rainfall is based however on the records of 52 stations, and it is not possible to obtain their data for June to September at the beginning of October. Hence another forecasting formula was obtained replacing Upper Siam rainfall by Northwest India rainfall. The relations with the latter were analysed by working out the C.Cs. with the rainfall of the individual months of the monsoon season. The C.Cs. obtained were June —·03, July —·13, August —·35 and September ·09. As the greater proportion of the rainfall of Northwest India falls in the months July and August, this period with its C.C. of —·33 was finally selected. The following table of co-efficients was then formed.

	S. America pressure June to August.	Bangalore westerly upper winds 3 to 5 kms., September.	Agra westerly upper winds 5 to 8 kms., September.	Northwest India rainfall July and August.
South Madras rainfall October to December.	—·40	—·38	+·29	—·33
S. America pressure	..	—·05	—·13	+·35
Bangalore winds	..	..	—·08	—·16
Agra winds	..	..	..	—·28

The resulting regression equation is—

[South Madras rain] = —·32 [S. America pressure]
—·42 [Bangalore winds]
+·14 [Agra winds]
—·24 [N. W. India rain]

with a multiple C.C., R = ·64 .. .. (II)

It is seen that the replacement of Upper Siam rainfall by Northwest India rainfall with its smaller C.C. has made no appreciable difference in the multiple C.C.

It can be seen from the table of co-efficients of the two preceding regression equations that both Upper Siam rainfall and Northwest India rainfall have moderately high correlation coefficients with South America pressure and Agra Upper winds. Another table of co-efficients was formed in which neither N. W. India rainfall nor Siam rainfall was included. In this table which is given below the C.C. with South America pressure was based upon the same period, 1914 to 1938,

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In equations I to IV in this paper, by putting an element within double brackets we indicate proportional departures, *i.e.*, the ratio of the departures to their standard deviations.

as the C.C. with Agra Upper winds. The C.C. with Bangalore is based upon the period 1915 to 1938 as no data are available for 1914.

	S. America pressure June to August.	Bangalore westerly upper winds 3 to 5 kms., September.	Agra westerly upper winds 5 to 8 kms., September.
South Madras rainfall October to December ..	—·40	—·38	+·29
S. America pressure	..	—·05	—·13
Bangalore winds	..	..	—·08

The resulting formula is—

[South Madras rain] = —·39 [S. America pressure]
— ·38 [Bangalore winds]
+·21 [Agra winds]

with a multiple C.C., R = ·60 .. .. (III)

The addition of N. W. India rainfall to the above table, basing the C.C. on the same period 1914 to 1938, did not lead to any appreciable change in the multiple C.C. It would appear therefore that no appreciable loss is suffered by the omission of N. W. India rainfall from the forecasting formula.

The values calculated with above formula and the actual values are plotted in *Fig. 2.*

Using the three factors, South America pressure, Bangalore upper winds and Agra upper winds, for the period 1914 to 1938, a forecasting formula was derived for Southeast Madras alone. The table of co-efficients was—

	South America pressure June to August.	Bangalore westerly upper winds 3 to 5 kms., September.	Agra westerly upper winds 5 to 8 kms., September.
Southeast Madras rainfall, October to December ..	—·39	—·37	+·30
S. America pressure	..	—·05	—·13
Bangalore winds	..	..	—·08

The resulting formula is—

[Southeast Madras rainfall] = —·38 [South America pressure]
—·37 [Bangalore winds]
+·22 [Agra winds]

with the multiple C.C., R = ·59 .. .. (IV)

The multiple C.C. for forecasting Southeast Madras rainfall is thus practically the same as the multiple C.C. for forecasting South Madras rainfall, and justifies the combination of the two areas for purposes of forecasting.

The values calculated with above formula and the actual values are plotted in *Fig. 3.*

Discussion.

In formulae (I) and (II) the number of years on which the C.Cs. are based are not the same for all factors, varying from 24 to 64 years. In formulæ (III) and (IV) however they are based upon practically a common period of 25 years. For purposes of testing the significance of the multiple C.Cs. we may accept the 25 years for all the four. It is found from Wishart's table (^{3}) that the 5 per cent. and 1 per cent. values of R, (N=25, n=4), are 0·60 and 0·69 respectively, while similar values of R, (N=25, n=3), are 0·55 and 0·59 respectively. It is seen that the first two multiple C.Cs. fall between the 5 per cent. and 1 per cent. values, whereas the last two are equal to or just above the 1 per cent. values. The last two co-efficients may be considered significant.

It will be seen from the graphs in Figs. 2 and 3, that of the twenty-six years for which values have been plotted, there is a fairly close agreement between the calculated and actual values in twenty-one years, and that the actual values depart widely from the calculated values only in the years 1920, '22, '26, '27 and '38. An examination of the weather charts for these years shows that the large excesses in 1920 and '22 are caused by exceptionally heavy rainfall associated with the November storms of those years, while the large defects in the other three years, are due in the first instance to the late commencement of the northeast monsoon rains, and secondly to the fact that the November storms took a more northerly course than usual towards the north of the Peninsula or northeast India with the result that the monsoon was very weak in the south of the Peninsula.

In conclusion I wish to express my thanks to Mr. Satakopan for the help received during the progress of this investigation.

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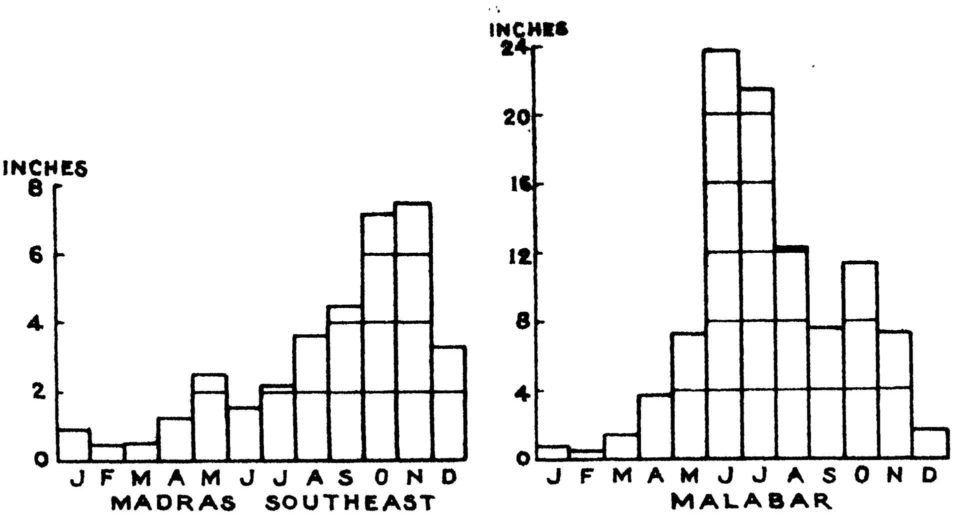

Fig. 1. Histograms of normal rainfall.

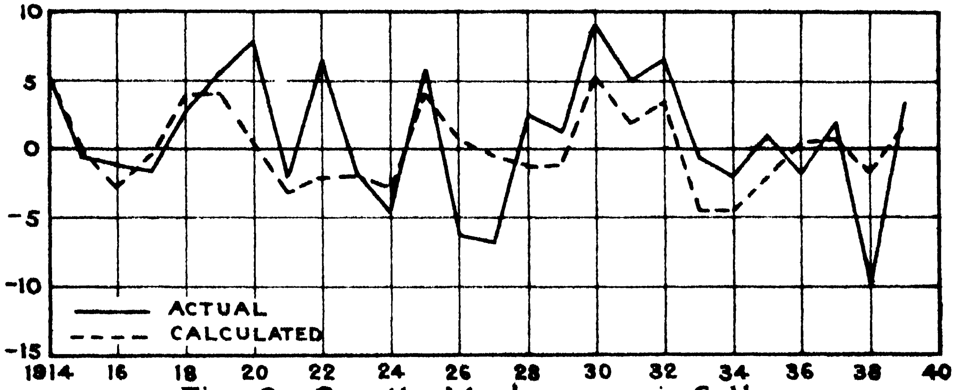

Fig. 2. South Madras rainfall.
OCTOBER TO DECEMBER.

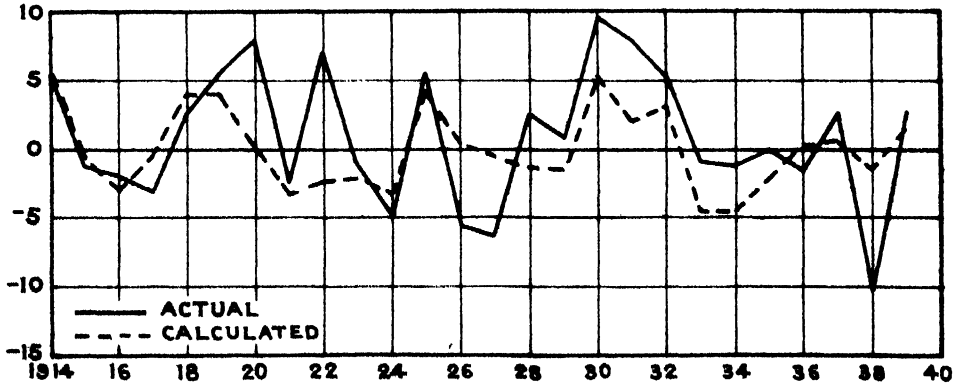

Fig. 3. Southeast Madras rainfall.
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V. DORAISWAMY IYER.

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Diurnal variation of rainfall at Colaba (Bombay) from an analysis of hourly rainfall records.

BY

V. DORAISWAMY IYER.

(*Received on 9th October 1940.*)

Abstract.—The hourly rainfall records obtained with the photographic self-recording rain-gauge at the Colaba Observatory for the sixty years 1875 to 1934 have been utilised for a discussion of the diurnal variation of rainfall at Bombay. Tables showing two-hourly rainfall amounts and occasions of rain are given. In the monsoon season the period of the day, midnight to noon, gets more rain than the subsequent twelve hours. In the dry season there is more rainfall at night than in the day time.

The relation of rainfall to wind direction have been discussed with the help of the data of the ten years 1925 to 1934. It is seen that in the monsoon months the wind directions with which the largest amounts of rainfall and the largest number of occasions of rain are associated are the prevailing directions. The 'probability of rain' with wind of any direction, however, appears to be greatest when it is nearly opposite the prevailing direction and least when it approaches the prevailing direction.

Introduction.

The rainfall recorded at the Colaba Observatory, Bombay, during the years 1843 to 1874 has been discussed at length by Chambers (1). He has given a small table showing the ratios of falls at individual hours to the average hourly fall. Daily normals of rainfall based on data up to 1920 have been published by Banerji (2). In addition to a table of monthly normals, curves showing the daily normals of rainfall and annual falls from 1846 to 1937 have been given by Ramanathan (3). The diurnal variation of rainfall has not been discussed in detail so far, and it seemed therefore worthwhile analysing the available hourly rainfall records with a view to understand this feature in different seasons of the year.

Seasons at Bombay.—The division of the year into a dry and wet season is strongly marked in Bombay. The wet season begins with the setting in of the monsoon early in June and lasts till its withdrawal in the middle of October. The monsoon shows its greatest activity in the month of July which together with June, receives 61 per cent. of the annual fall of 71". There is a marked decrease of rainfall from July to August and a further decline in September; these two months get about 34 per cent. of the annual fall. Another sharp fall occurs in passing from September to October and the latter month receives only 3 per cent. of the annual fall. The rainfall recorded in the remaining seven months is only 2 per cent. of the annual fall, and of these the greater portion falls in the months of November and May. The rainfall in May is usually associated with thunderstorms, mostly in the latter half of the month before the burst of the monsoon, while the rain in November is generally the sequence of the occasional passage inland of a depression from the Bay or is associated with a storm in the Arabian Sea which after re-curving approaches the Bombay-Kathiawar coast.

The self-recording rain-gauge at Colaba.

A photographic recording rain-guage was installed at Colaba by Chambers in 1873. A detailed description of the instrument is given in Appendix V to the "Bombay Magnetical and Meteorological Observations, 1865-70". A shorter description is also found on pp. xlvi to xlix of the Introduction to the "Bombay Magnetical and Meteorological Observations 1871-78". The following is extracted from the latter source.

For the self-recording part of the rain-gauge the photographic arrangement of the thermograph is made use of; it is worked with the same light, and the record is received on the same paper. The indicating part of the instrument consists essentially of a U shaped tube; in its longer and wider limb the rain water is received, and mercury fills the other shorter and narrower limb as well as the bent part of the U tube. As the water accumulates in the wide limb, the mercury rises in the narrow one, and the measurement of the changes of level in the latter serves to determine the rate and quantity of rainfall. When the water reaches a certain height in the wide limb, it is emptied by means of a syphon down to a certain fixed level, and then the filling proceeds as the rainfall continues. The height of the mercury in the short limb of the tube is photographed.

The funnel which receives the rain is erected on the roof of the thermograph-shed at a height of 4·4 ft. above the ridge, 28 ft. above the ground, and 62 ft. above mean sea level, and its diameter measures exactly 8 inches at a temperature of 60°F. The weight of half an inch depth of rain water falling into this funnel would be about 6,334 grains and the short leg of the syphon is made of such a length that very nearly this quantity of water is discharged each time the syphon comes into action. The lens is placed in such a position that the displacement of the image of the mercury level for each discharge is nearly half an inch. The time marks are made every two hours by cutting off the light for four minutes, from exactly two minutes before every even hour to exactly two minutes after the hour.

Method of Tabulation of the record.—Details regarding the tabulation, etc., are found on pages xi and xii of the Introduction to the volume of "Magnetical, Meteorological and Seismographic Observations," 1916 to 1920. It may be stated briefly that the tabulations are made with the true inch scale of the thermograph tabulating instrument, using the white line as the datum. The glass scale attached to the instrument has two lines, and when one of these is adjusted to lie on the time mark made at each even hour by cutting off the light, the other line marks the odd hour. The readings of the curve corresponding to the time marks and the second line of the glass scale give the readings at the even and odd hours respectively.

The rainfall for each hour read off from the curve is entered in the hourly tabulation sheets with a column for each hour. The monthly totals of these rainfall columns give the amount of rain which has fallen in each hour of the day, while by counting the number of entries in each column the number of hours with rain or 'rain hours' in each hour of the day is obtained. The data for the sixty years 1875 to 1934 are utilised in the present discussion.

Catch of the self-recording rain-gauge compared with that of the Newman rain-gauge.—As already stated the funnel of the self-recording rain-guage is situated at a height of 28 ft. above the ground. The standard Newman rain-gauge has its funnel at a height of 4½ ft. above ground. The average rainfall amounts for the same period of 60 years 1875 to 1934, for the two rain-guages are given below together with the ratio between the catches of the two gauges. It can be seen that on the mean of the year the ratio is 95 per cent. This does not differ appreciably from the ratio, 94 per cent. between gauges at 5 ft. and 25 ft. at Rotherham based upon 8 years' observations(4).

TABLE I.—*Average monthly rainfall (1875-1934).*

	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Year.
A—Newman rain-gauge 4½ ft. above ground.	0·14	0·07	0·05	0·03	0·71	18·84	24·19	13·20	10·97	2·40	0·50	0·08	71·18
B—Self recording rain-gauge 28 ft. above ground.	0·12	0·06	0·05	0·03	0·66	18·13	23·23	12·37	10·69	1·98	0·45	0·08	67·85
B/A × 100 ..	86	86	100	100	93	96	96	94	97	83	90	100	95

A curious anomaly in the hourly totals of rainfall and its explanation.—The amount of rain as well as of 'rain hours' in each hour of the day for each of the twelve months were added together for the sixty years 1875 to 1934, and the totals for the sixty years were obtained. When they were plotted for the wet months, the diurnal variation curves exhibited a curious bi-hourly cycle with higher values for the even hours than for the odd hours; the curves for the monsoon season June to October as a whole are shown below.

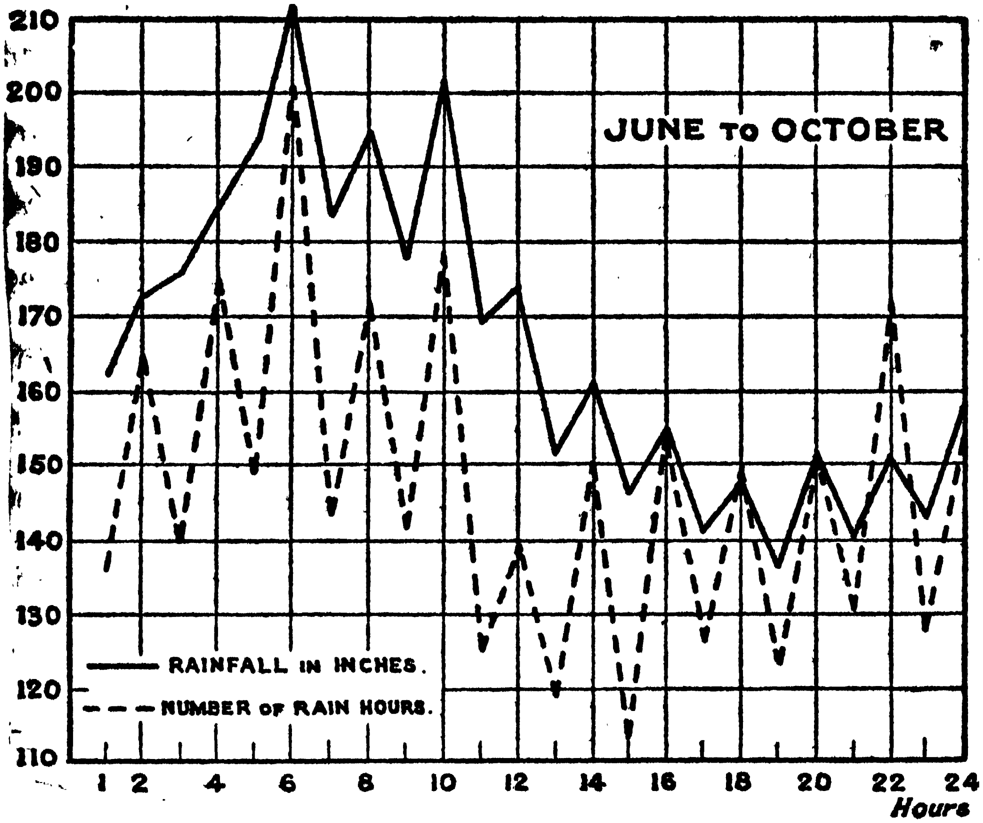

Fig. I.—Hourly values of rainfall and of number of 'rain hours' at Colaba (Bombay), June to October.

This indicated the probable existence of some systematic error in the tabulations. On this being pointed out, Dr. Ramanathan, then Director of the Colaba Observatory, critically examined the methods of tabulation and found that the distance between the even hour line and odd hour line of the glass scale was only 9·0 mm., while the distance between the two even hour marks on the rainfall curve was 18·7 mm. The two-hourly intervals of the rainfall curve were therefore getting systematically divided into two unequal halves in the ratio of 9·0 to 9·7, the hourly intervals 1 to 2, 3 to 4, 5 to 6, etc., being longer.

The following table which gives the total amounts of rainfall as tabulated at all hourly intervals ending at odd hours, 0 to 1, 2 to 3, etc., and the total amounts as tabulated at all hourly intervals ending at even hours, 1 to 2, 3 to 4, etc., supports the ratio found on the glass scale.

TABLE II.

	June.	July.	August.	September.	October.	June to October.
A—Total rainfall 1875-1934 at all intervals ending at odd hours, 0-1, 2-3, etc.	524·7	679·9	347·3	309·4	57·3	1918·5
B—Total rainfall at all intervals ending at even hours, 1-2, 3-4, etc.	563·1	713·9	394·7	332·1	61·4	2065·2
B/A × 9·0	9·7	9·5	10·2	9·7	9·7	9·7

The error in bisecting the two-hourly intervals made it therefore necessary to consider the rainfall amounts not in each hour but in each two-hourly interval. Hence the amounts of rainfall in the hours 0 to 1 and 1 to 2 were added together. Similarly for other two-hourly intervals ending at even hours. The number of 'rain hours' were also similarly added together.

Diurnal variation of rainfall and of 'rain hours.'

Table VI gives for each month and the year the total rainfall amount in inches and the number of 'rain hours' in each two-hour period of the day.

The wet season which becomes established with the onset of the monsoon may be considered first. There is a clear diurnal variation of rainfall in the months June to September, the difference between the maximum and minimum two-hourly amounts being about 36 per cent. of the average in the months June to August and 70 per cent. of the average in September. The earlier half of the day, midnight to noon, gets more rain than the latter twelve hours. The diurnal variation is greater in October, the daily range of the two-hourly rainfall amount increasing to about 130 per cent. of the average : there is a difference from the previous months in the distribution of rain during the day ; the later evening hours become a period of maximum raininess and this is continued during the night. As a result nearly two thirds of the day's rain falls during the night hours.

The following table gives the mean rainfall in different periods of the year in each of the four quarters of the day.

TABLE III.—*Mean rainfall per year.*

Period.	0 hrs.—6 hrs.	6 hrs.—12 hrs.	12 hrs.—18 hrs.	18 hrs.—24 hrs.
June to September	17·8	17·9	14·8	14·0
October	0·61	0·46	0·27	0·64
November to May	0·35	0·30	0·28	0·42

The number of 'rain hours' also behave similarly, as is shown by the table below giving the number of 'rain hours' per year in each quarter of the day in different periods of the year.

TABLE IV.—*Mean number of 'rain hours' per year.*

Period.	0 hrs.—6 hrs.	6 hrs.—12 hrs.	12 hrs.—18 hrs.	18 hrs.—24 hrs.
June to September	155	146	132	137
October	5·8	3·5	2·9	6·3
November to May	4·4	3·1	2·7	3·9

In the dry months, November to May, the rainfall amounts are small, but the diurnal variations are well marked. The normal rainfall in November is only half an inch; in the five months December to April together it is only 0·3 of an inch. In all these months (except January), there is more rainfall at night than during the day; in January the influence of the very occasional disturbances seems to have masked the general tendency. February, March, April and May show the favourableness of night very clearly.

It appears from the above that the diurnal variation of rainfall at Bombay, as may be expected from its position on the windward side of the land area during the monsoon season, is mainly of the oceanic type, with increased rainfall at night and in the morning hours and a decreased rainfall in the afternoon hours.

Average hourly intensity of rainfall.—The average hourly intensity of rain obtained by dividing the total amount of rain in each two-hourly interval by the corresponding number of 'rain hours' was calculated for each of the months. The maximum and minimum average intensities are given in the table below for each month of the year. There is a large variation of average intensity in the months January to May. In the monsoon months June to September the variation is small. The variation in average intensity again increases from October.

TABLE V.

Average hourly intensity of rain.

	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
Maximum	0·20	0·18	0·20	0·22	0·20	0·17	0·13	0·11	0·14	0·16	0·16	0·13
Minimum	0·01	0·01	0·01	0·01	0·06	0·12	0·10	0·07	0·10	0·07	0·07	0·03

Frequency of heavy rainfall.—The heaviest rainfall in one hour in each month was culled from the hourly tabulations for each of the sixty years 1875 to 1934. From these figures a frequency table was prepared, for values of rainfall increasing in steps of a quarter of an inch, giving the number of occasions in which the heaviest rainfall recorded was between 0·01" to 0·25", 0·26" to 0·50", etc. This frequency table is reproduced in *Table X*, as the intensity of rainfall in short periods is a matter of interest to Drainage Engineers in cities.

Relation of rainfall to wind direction.

The hourly direction of the wind in 16 points of the compass for each day of the year and the hourly rainfall, for each day on which rain fell obtained from the photographic recording rain-gauge, are being published in the 'annual volumes of observations at Bombay' from the year 1924. These data for the ten years 1925 to 1934 were utilised for classifying the rainfall according to the wind direction during the hour of rain. The rainfall recorded in any hour was entered in a column corresponding to the wind direction in that hour. The monthly totals of these columns gave for each month the total amount of rain associated with the winds from each of the 16 points of the compass: separate columns were provided for calms and variable winds. A simple count of the number of entries in each of these columns gave the number of 'rain hours' with winds from different directions. The data tabulated as above are given in *Table VII.* They are also plotted as wind roses in *Fig. 2.*

In January the largest amount of rain fell with an ESE wind, while the largest number of 'rain hours' was associated with a N wind. The months February to April were absolutely dry in the ten years examined. During May, about 60 per cent. of the rainfall and of 'rain hours' were associated with winds between S and W; but while the maximum rainfall occurred with a SSW wind, the 'rain hours' were almost equally distributed between SW and SSW.

In June 60 per cent. of the rainfall and 70 per cent. of the 'rain hours' were associated with winds between S and W, and the direction of the maximum was WSW for both the elements. In July and August, when the monsoon is strongest, the westerly directions between WSW and WNW were associated with 70 per cent. to 75 per cent. of rainfall and 75 per cent. to 80 per cent. of 'rain hours', but there is a veer of the direction of the maximum in passing from July to August. With the weakening of the monsoon in September, there is less concentration about the direction of the maximum, WNW; directions from W to NW account for only about 50 per cent. of the rainfall and 45 per cent. of 'rain hours'. During October both the rainfall and the 'rain hours' were fairly evenly distributed over all points of the compass.

During November, there is a concentration in the northeastern quadrant, the directions between NNE and ENE accounting for 55 per cent. to 65 per cent. of the rainfall and of 'rain hours'. In December, nearly all the rain fell with winds from between NE and SE. It would appear that in these two months rain falls generally in Bombay when a low pressure area, whether approaching from the Bay across the Peninsula, or advancing northwards in the Arabian Sea, is to the south of Bombay.

An inspection of the wind roses in *Fig. 2* shows that the direction of wind associated with the maximum amount of rain is ESE in January, SSW in May, WSW in June, W in July, WNW in August and September, N in October, NNE in November and NE in December; thus there appears to be a clockwise rotation of this direction with the advance of the year. In the case of 'rain hours' also a similar rotation is apparent, though it is less regular.

The average intensities of rainfall, when it occurs with winds from different directions were obtained by dividing the rainfall under the different heads in *Table VII* by the corresponding number of 'rain hours'. During the monsoon months, June to October, the greatest intensity appears to be associated with variable winds except in the month of September. The winds next in order of importance are generally from the northerly quadrant except in August, when winds from S or SSE are associated with greater intensity than northerly winds. In May and December northeasterly winds are associated with maximum intensities, while in January and November high intensities occur with winds from a southeasterly direction.

In the preceding discussion of rainfall associated with winds from different directions, the average frequencies of winds from different directions were not considered. It appeared desirable to do so at least for the months June to October when 98 per cent. of the rainfall of Bombay is received. Accordingly the hourly wind directions of those months for each of the ten years 1925 to 1934 were classified under the sixteen points of the compass. The total number of hours of wind from the sixteen points in the ten years is given in *Table VIII* and is also plotted as wind roses in *Fig. 3.*

A comparison of these wind roses with those in *Fig. 2* shows a striking similarity in the months June to September. The maximum number of hours of wind and of rain hours are from directions between WSW and WNW. The largest amounts of rain also fall with winds from those directions. On account of their greater prevalence, the westerly winds of this season are associated on the whole with more rainfall and number of rain hours than winds from other directions. It does not however appear that this is so in proportion to their frequency; for if we estimate the wetness of the winds by the proportion of the number of hours of winds which are accompanied by rain to the total number of hours of winds, we get a different picture.

The number of hours of rain associated with wind from each direction given in *Table VII* was expressed as a percentage of the total number of hours of wind from the same direction given in *Table VIII.* These figures of percentage probability of rain with wind from each direction are given in *Table IX*; they are also shown as wind roses in *Fig. 4.*

A comparison of the figures in *Tables VIII and IX* and the corresponding wind roses in *Figs. 3 and 4* is interesting. In June, July and October the maximum probability of rain occurs with a wind which has the least frequency, while in the other two months, the maximum probability is associated with a wind frequency, which though not the minimum is not far removed from it. The maximum wind frequency is associated with a minimum probability of rain in July and October, and with a probability but a few steps removed from the minimum in June and September. In August, however, the maximum wind frequency is associated with a fairly high probability of rain, the minimum probability of rain in this month occurring with a wind frequency not far removed from the minimum. Thus generally the probability seems to be greatest when the wind direction is nearly opposite the prevailing wind direction, and least when it approaches the prevailing direction. Hence the statement made by Blanford in the case of Calcutta that "It is not when the monsoon current is blowing steadily that rain is most probable, but when it is deflected from its normal direction by some local irregularity of pressure, and rain is the more probable in proportion as this deflection is greater" seems to be equally applicable to Bombay.

I am indebted to Dr. Ramanathan for the loan of the Ms. records and for helpful suggestions in writing up the paper.

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TABLE VI.

Total rainfall in inches and number of 'rain hours' in each two-hourly period of the day at Colaba (Bombay) in the 60 years 1875 to 1934.

	0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	Total.
January	0·36 *5*	0·10 *7*	0·19 *5*	1·17 *13*	3·17 *16*	0·48 *8*	0·71 *7*	0·31 *6*	0·68 *7*	0·06 *2*	0·09 *3*	0·11 *2*	7·43 *81*
February	0·42 *4*	0·46 *4*	1·10 *6*	0·28 *3*	0·11 *3*	0·56 *8*	0·06 *5*	0·27 *7*	0·17 *4*	0 *0*	0·10 *2*	0·03 *1*	3·56 *47*
March	0·40 *4*	0·33 *5*	0·13 *7*	0·20 *3*	0·07 *2*	0 *0*	0·03 *2*	0·04 *1*	0 *0*	0 *0*	0·81 *4*	0·76 *5*	2·77 *33*
April	0·20 *4*	0·89 *4*	0·29 *9*	0·05 *2*	0·32 *4*	0·04 *1*	0 *0*	0 *0*	0 *0*	0 *0*	0·02 *2*	0·15 *4*	1·96 *30*
May	2·87 *35*	3·66 *37*	2·53 *42*	1·37 *30*	0·93 *14*	1·98 *17*	2·15 *11*	0·83 *17*	4·34 *26*	3·27 *33*	6·73 *28*	2·98 *33*	33·64 *323*
June	93·11 *654*	102·32 *706*	110·39 *765*	102·31 *654*	104·05 *683*	95·31 *567*	76·51 *545*	83·05 *560*	78·56 *605*	77·33 *611*	83·95 *672*	80·87 *626*	1087·76 *7648*
July	114·96 *1018*	116·94 *1038*	120·99 *1154*	125·69 *1038*	133·85 *1074*	122·91 *964*	122·23 *994*	122·80 *1000*	102·68 *980*	94·62 *916*	96·89 *995*	110·27 *978*	1393·83 *12149*
August	57·21 *749*	64·86 *786*	73·49 *879*	71·07 *814*	69·51 *846*	70·74 *673*	67·11 *733*	56·88 *712*	55·87 *715*	50·08 *651*	49·57 *746*	55·65 *679*	742·04 *8983*
September	54·61 *472*	65·97 *517*	81·60 *582*	69·02 *550*	60·49 *525*	46·79 *387*	43·67 *377*	35·14 *346*	42·08 *373*	50·05 *439*	49·47 *481*	42·54 *408*	641·43 *5457*
October	15·09 *124*	10·57 *110*	10·76 *114*	8·69 *92*	11·40 *70*	7·45 *51*	3·31 *43*	3·46 *51*	9·55 *83*	16·04 *130*	10·78 *128*	11·58 *117*	118·68 *1113*
November	1·70 *23*	1·34 *20*	2·91 *25*	2·44 *17*	2·61 *17*	0·99 *14*	1·20 *18*	1·42 *15*	3·42 *22*	2·87 *31*	3·69 *37*	2·50 *30*	27·18 *269*
December	0·25 *4*	0·16 *6*	0·88 *10*	0·34 *7*	0·59 *5*	0·17 *2*	0·24 *5*	0·59 *7*	0·18 *5*	0·25 *5*	0·90 *7*	0·12 *4*	4·67 *67*
Year	341·18 *3096*	367·60 *3240*	414·26 *3598*	382·63 *3223*	387·10 *3259*	347·42 *2692*	317·31 *2740*	304·79 *2722*	297·53 *2820*	294·57 *2818*	303·00 *3105*	307·56 *2887*	4064·95 *36200*

TABLE VII.

Total rainfall in inches and number of rain hours associated with winds from each of the 16 points of the compass at Colaba (Bombay) in the ten years 1925 to 1934.

	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Calm or variable.
January	0·19 *5*	0·45 *2*	0·01 *1*	.. ..	.. ..	1·87 *3*	0·21 *1*	.. ..	0·03 *1*	.. ..	.. ..	.. ..	.. ..	0·04 *1*	0·13 *2*	.. ..	.. ..
May	.. ..	0·76 *2*	0·01 *1*	.. ..	0·72 *3*	0·11 *4*	0·18 *4*	0·74 *6*	0·37 *2*	1·86 *12*	0·66 *13*	0·50 *8*	0·64 *5*	0·08 *3*	0·02 *1*	0·20 *2*	.. ..
June	3·07 *13*	1·17 *7*	1·53 *8*	0·83 *8*	2·76 *9*	3·10 *21*	7·45 *46*	11·94 *96*	11·76 *86*	20·19 *168*	28·97 *254*	39·41 *299*	24·93 *145*	25·74 *131*	11·13 *45*	6·37 *25*	1·32 *4*
July	2·69 *15*	0·63 *1*	2·20 *6*	2·74 *8*	0·26 *2*	1·30 *6*	2·45 *19*	4·95 *35*	2·63 *24*	7·95 *76*	19·51 *221*	45·31 *623*	54·76 *538*	48·70 *378*	16·85 *106*	5·67 *12*	2·07 *3*
August	0·03 *1*	0·03 *1*	0·08 *2*	0·22 *5*	0·10 *2*	0·11 *4*	0·05 *3*	1·31 *7*	2·24 *9*	1·65 *29*	7·15 *132*	21·68 *444*	27·14 *451*	41·74 *373*	11·21 *90*	3·73 *22*	1·17 *1*
September	2·29 *35*	4·98 *21*	3·16 *23*	2·25 *19*	1·51 *16*	1·70 *27*	2·40 *36*	0·74 *16*	0·73 *14*	2·87 *43*	9·65 *66*	7·58 *99*	20·00 *101*	19·94 *171*	16·11 *113*	12·33 *50*	0·34 *4*
October	5·17 *13*	0·94 *7*	2·65 *10*	2·02 *12*	4·11 *14*	1·17 *16*	2·34 *28*	1·02 *12*	1·77 *15*	3·22 *24*	3·90 *20*	1·13 *14*	2·28 *21*	1·58 *15*	2·19 *20*	2·15 *21*	1·03 *2*
November	0·07 *4*	3·19 *18*	2·93 *24*	1·81 *14*	0·33 *4*	0·65 *8*	1·28 *5*	0·36 *5*	0·06 *3*	0·37 *3*	0·25 *2*	0·03 *1*	.. ..	0·13 *2*	0·04 *1*	0·12 *3*	0·01 *1*
December	.. ..	0·07 *2*	0·56 *5*	0·25 *4*	0·27 *6*	0·24 *4*	0·06 *3*	.. ..	.. ..	.. ..	.. ..	.. ..	.. ..	.. ..	.. ..	.. ..	.. ..

TABLE VIII.

Number of hours of wind from the sixteen points of the Compass at Colaba (Bombay) in the ten years 1925 to 1934.

	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Calm.
June	28	15	21	34	22	66	210	413	378	835	974	1653	983	1003	445	113	7
July	21	1	6	10	7	13	40	77	73	221	834	2709	1945	1148	306	24	5
August	39	23	38	27	24	21	20	35	31	132	683	2251	2084	1362	450	215	5
September	186	133	213	149	109	202	291	211	170	259	428	787	768	1326	1205	739	18
October	653	377	606	758	326	428	453	174	131	260	213	177	228	587	918	1137	14

TABLE IX.

Percentage probability of rain with winds from the sixteen points of the compass at Colaba (Bombay).

June	46	47	38	24	41	32	22	23	23	20	26	18	15	13	10	22	57
July	71	100	100	80	29	46	47	45	33	34	26	23	28	33	35	50	60
August	3	4	5	19	8	19	15	20	29	22	19	20	22	27	20	10	20
September	19	16	11	13	15	13	12	8	8	17	15	13	13	13	9	7	22
October	2	2	2	2	4	4	6	7	11	9	9	8	9	3	2	2	14

TABLE X.

Frequencies of heaviest rainfall in one hour in the years 1875 to 1934.

	0·01—0·25.	0·26—0·50.	0·51—0·75.	0·76—1·00.	1·01—1·25.	1·26—1·50.	1·51—1·75.	1·76—2·00.	2·01—2·25.	2·26—2·50.	2·51—2·75.	2·76—3·00.	3·01—3·25.	3·26—3·50.	3·51—3·75.	3·76—4·00.
January	9	1	..	..	..	..	..	1	..	..	..	..	..	..	..	..
February	13	..	1	..	..	..	..	..	..	..	..	..	..	..	..	..
March	10	1	..	..	..	..	..	..	..	..	..	..	..	..	..	..
April	7	1	..	..	..	..	..	..	..	..	..	..	..	..	..	..
May	18	5	2	..	1	..	1	..	..	..	..	..	..	1	..	..
June	..	..	6	9	11	7	6	6	5	3	3	1	2	..	..	..
July	..	3	4	17	7	12	7	1	3	2	3	1	..	..	..	..
August	2	14	15	10	6	7	3	..	2	..	..	..	1	..	..	..
September	..	7	13	11	7	6	8	1	2	2	2	..	..	..	..	1
October	15	11	3	8	5	3	2	..	..	..	..	..	..	..	..	..
November	16	6	3	2	2	..	..	..	..	..	..	..	..	..	..	..
December	4	3	..	..	..	..	..	..	..	..	..	..	..	..	..	..
June—October	17	35	41	55	36	35	26	8	12	7	8	2	3	..	..	1

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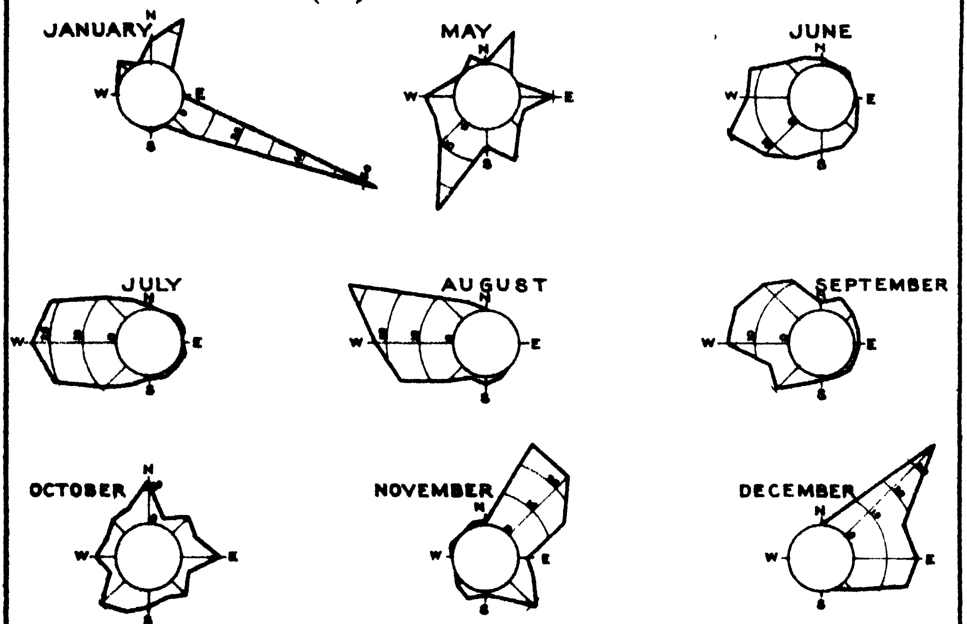
Plate I

(*a*) RAINFALL



(*b*) RAIN-HOURS

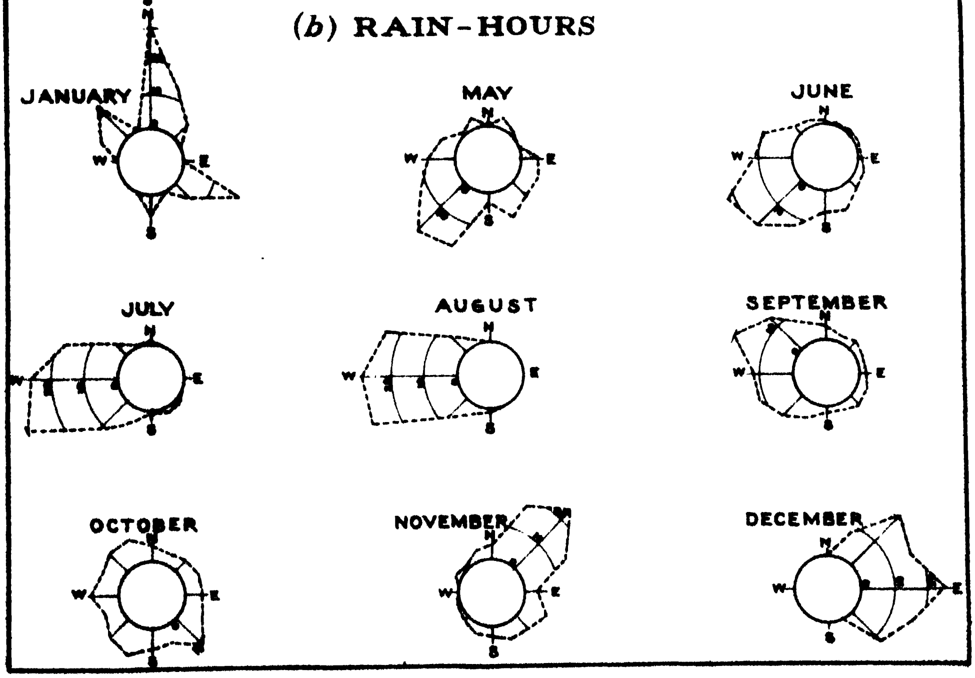


FIG. 2 WIND ROSES SHOWING (a) THE RAINFALL AMOUNTS AND (b) FREQUENCY OF RAIN-HOURS ASSOCIATED WITH DIFFERENT DIRECTIONS OF WIND.

Plate II

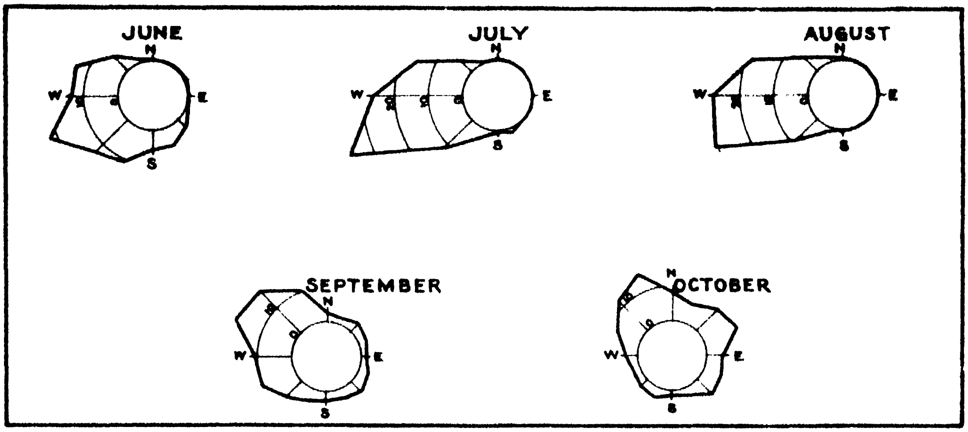


FIG. 3. WIND ROSES SHOWING AVERAGE FREQUENCIES OF WIND (ALL DAYS) FROM DIFFERENT DIRECTIONS IN THE MONSOON MONTHS.

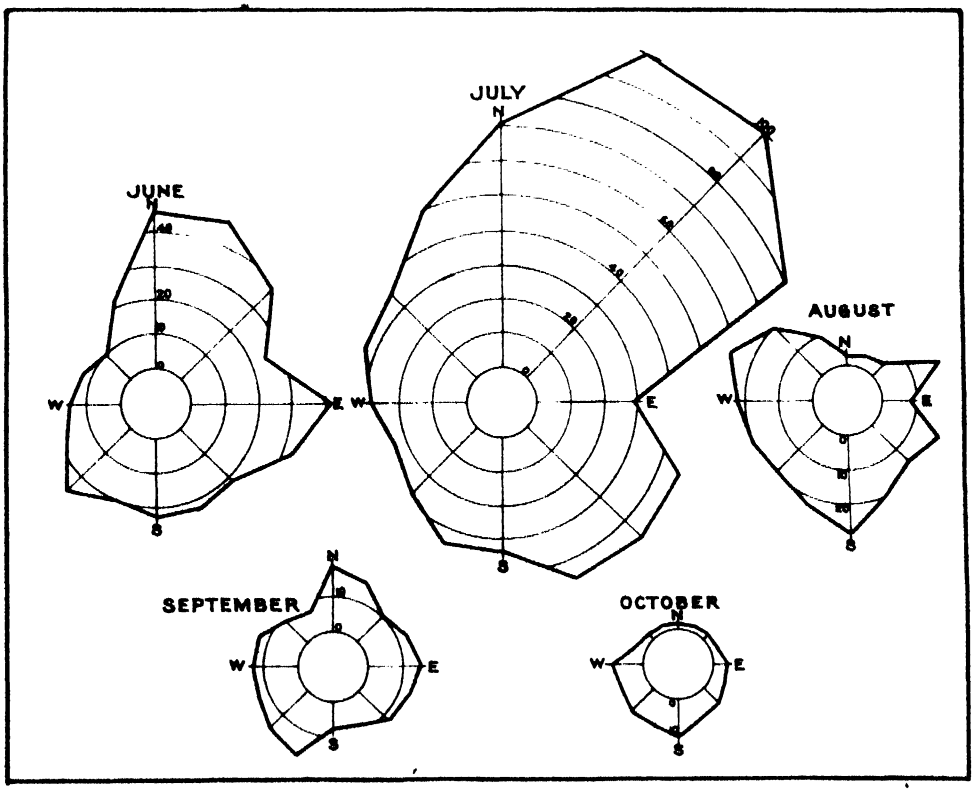


FIG. 4. WIND ROSES SHOWING THE PERCENTAGE PROBABILITY OF RAIN WITH WINDS FROM DIFFERENT DIRECTIONS.

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Dust-Devil at Karachi on 28th February 1941.

BY

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AND

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(*Received on 28th November 1941.*)

Abstract.—Five photographs of a well formed dust-devil at Karachi Air Port on the 28th February 1941 have been given with a short description of its important features. The meteorological conditions on that day have been discussed briefly, making use of the tephigram drawn from the data available from an aeroplane met. flight made that morning.

Dust-devils are an interesting class of phenomena connected with local heat convection over dusty or sandy ground. Although known to occur frequently over the plains of northern India in summer few photographs of them are available. Extensive and interesting observations of whirl winds and duststorms near Lahore between 1847 and 1853 together with a number of sketches were published by Baddeley[1] in 1860. Hankin[2], Normand[3] and Veryard[4] have also dealt with this subject in later years. The purpose of this paper is to present five photographs, taken by the authors, of a very well marked dust-devil which occurred at Karachi Air Port on 28th February 1941 and discuss briefly the meteorological conditions on that day.

On the 28th February 1941, three well marked dust-devils were seen at Karachi Air Port between 2-20 and 3-40 P.M. having formed apparently in the sandy bed of the Malir river about 2 miles to the southeast of the civil aerodrome and moving northwest. The second of these, which was the best formed and the biggest, was photographed from the southern portico of the Administrative building of the Civil Aerodrome. The photographs are shown in *Figs 2 to 6*. The first was taken at about 3 P.M. and the , later ones at intervals of about 2 minutes as the dust-devil was moving towards the Administrative building. When the fifth photograph was taken it was only about 100 yards from the camera. The diameter of the whirl at the bottom was then estimated to be about 30 ft. and the whirling motion of wind and dust appeared very violent and in clockwise direction. The speed of movement of the dust-devil was 10 to 12 m.p.h. and its height was estimated to be about 3000 feet, the dust raised going up even higher and driven horizontally by the wind. The height was estimated by eye, a few prominent objects in the surrounding area like the Airship Shed providing a rough guide for comparison. The dust-devil was in the form of an inverted frustum of a cone with its narrow end on the ground. This is clear from each of the photographs, particularly the fourth and the fifth. It was a most impressive and awe-inspiring sight and was so well marked and high that it attracted the attention of R. A. F. personnel at the Aircraft Depot about 4 miles away. It picked up considerable dust as it moved along and the lowest portions looked almost black with dust. Some persons who walked through the dust-devil stated that as they entered it there was a feeling of suffocation with dust and the whirling motion of the wind; but in the central area the wind and dust were perceptibly less than in the outer annulus.

Baddeley has recorded that in many dust-devils he found the central region calm or with very light winds while round about the winds were blowing in every direction. Others have also recorded similar observation.* This comparatively calm and dust-free innner core of the dust-devil has been explained to be due to the centrifugal force driving the wind and dust away from the centre of the vortex to such a distance where that force balances those of the incoming currents into the vortex.

As regards the form of dust-devils, Baddeley states "I have witnessed hundreds of whirlwinds but never saw anything resembling an inverted cone," (*i.e.*, with the horizontal extent of the higher portions greater than the lower portions) and says "the essential portion of the whirlwind always appeared to me, in the plains of India, as a lofty cylindrical pillar preserving apparently the same diameter throughout its entire height for thousands of feet". The dust-devil at Karachi was of the inverted conical shape even at the lower levels. Baddeley also records a train of dust extending from the dust-devil like the tail of a comet "invariably formed on the side corresponding with the working of the rotation and the line of progression". No such train of dust was observed in the Karachi dust-devil although it appears likely that on the side where the air from the surrounding region is fed into the vortex, a train of dust may be expected. Baddeley pictured a dust-devil as composed of an outer ring of ascending air carrying dust upwards and an inner core of descending air. Hankin also reports a dust-devil with a descending inner core. Pilots who have flown through well marked dust-devils do not however report having experienced any steady descending current, except the up and down movements constituting bumpiness.

It is well known that the one essential condition for the formation of dust-devils is a highly unstable condition of lower levels of the atmosphere near the ground. They are therefore generally known to occur on clear and nearly calm summer afternoons. According to Humphreys[5] "the flatter the region, the more barren, the hotter the surface and the quieter the air the more violent these whirls become". Dust-devils may be pictured as specially well marked local rising streams of heated air, rising as does air in contact with a heated plate, the whirling vortex motion being produced due to the surrounding air, which moves to replace the rising air, being directed to one side of the centre of the rising column.

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* See extracts quoted in para. 3 of Ind. Met. Mem. 22, pt. 7.

At Karachi summer afternoons are nearly always quite windy and gusty and therefore dust-devils are rare in that season. During October to March when much quieter wind conditions prevail, dust-devils occur on unusuallly warm and dry afternoons. The country outside Karachi town, particularly between the Civil Aerodrome and the Malir river, is flat, sandy and barren except for low shrubs. The sandy bed of the Malir river, which is dry except when there is heavy rain, which is very rare, appears to be a specially favoured locality for dust-devils to form. Dust-devils are known to be well marked and most frequent in regions where mirage conditions occur ; that is, when the lapse-rate of temperature in the lower levels near the ground exceeds the auto-convection lapse-rate which is 3½ times the dry adiabatic lapse-rate. Such high lapse-rates probably do occur at Karachi in the first 200 or 300 feet on unusually warm afternoons.

On the 28th February 1941, there was an anticyclonic distribution of pressure over northwest India with very little horizontal pressure gradient, light ground winds and generally clear skies. Maximum temperature was markedly above normal over northwest India both on the 27th and 28th. The air over Karachi on the 28th afternoon was dry and warm. Upper winds were from ENE/ESE up to 3 Kms. and from SE at 4 Kms. The autographic records of Karachi Air Port for 28th February—1st March 1941 are reproduced in *Fig. 7.* The 28th was an abnormally warm day, the maximum temperature (Karachi Air Port) being 94°F., 12°F. above normal and on the previous day 91°F. The solar radiation maximum temperature shown by a black-bulb thermometer was 166°F. on the 28th while it was 157F°. on the previous day. At Manora, an island near the coast about 13 miles to westsouthwest of the Civil Aerodrome, the maximum temperature on the 28th was 91°F., 11°F. above normal, that on the previous day being 80°F., 1°F. below normal. The air was dry and the wind generally light to moderate with the speed frequently dropping down to 2 to 4 m.p.h. between 2 and 4 P.M. when the dust-devils occurred. A short-lived sea breeze set in at about 7-15 P.M. with a fall of temperature and rise of humidity. The sky was clear in the morning except for some fine cirrus but about midday detached patches of cumulus characteristic of a well marked insolation day appeared. The cumulus clouds gradually increased towards evening and after sunset about three quarters of the sky was covered with cumulus. Late in the night lightning was seen towards southwest apparently over the sea area. A mild dry thunderstorm occurred over Karachi town sometime after midnight and the autographic records show that there was probably a thunderstorm at the Air Port too at about 1-15 A.M. of 1st March although none was observed or reported.

There are no observational data to show the extent of instability in the first few hundred feet above ground on the 28th afternoon. However, data obtained from an aeroplane meteorological flight made by the R. A. F. that morning show some useful information. The tephigram and the wet-bulb curve (estegram) drawn from the data (mean of ascent and descent observations—0835 to 0925 hrs.) are shown in *Fig. 1.* In the tephigram and estegram the first seven points refer to the ground level and successive 500 feet altimeter heights up to 3000 feet. The later points refer to successive 1000 feet altimeter heights. The tephigram shows that while there was the usual winter morning inversion up to 1000 feet, the lapse-rate of temperature above 1500 feet up to 8000 feet was fairly high. In the afternoon when the maximum surface temperature was 94°F., the tephigram up to 2000 feet was probably AB and the estigram CD and it may be presumed that at higher levels they remained unchanged. There was no change of air mass during the day and the diurnal variation of temperature and humidity at Karachi extends only up to about 2000 feet during the period October to March* and above that height the variation is small. The probable afternoon tephigram and estigram considered with respect to the dry adiabatic AE and the saturation adiabatic CF show instability for rising surface air up to 15000 feet with condensation occurring at 10000 feet. There was also superadiabatic lapse-rate (about 1½ times the dry adiabatic lapse-rate) up to 2000 feet. Considering that it was an abnormally warm day, it appears quite likely that in the first few hundred feet the lapse-rate was much higher and may have even exceeded the auto-convection lapse-rate.

9. Although dust-devils are generally not sufficiently extensive or severe as to be of much concern to aviation, a few pilots who have flown over or through well formed ones have reported severe bumpiness. If a landing aircraft gets into the lower portions of a well formed dust-devil the vertical motion may well upset it and cause a crash.

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* **Shown in a paper under preparation.**

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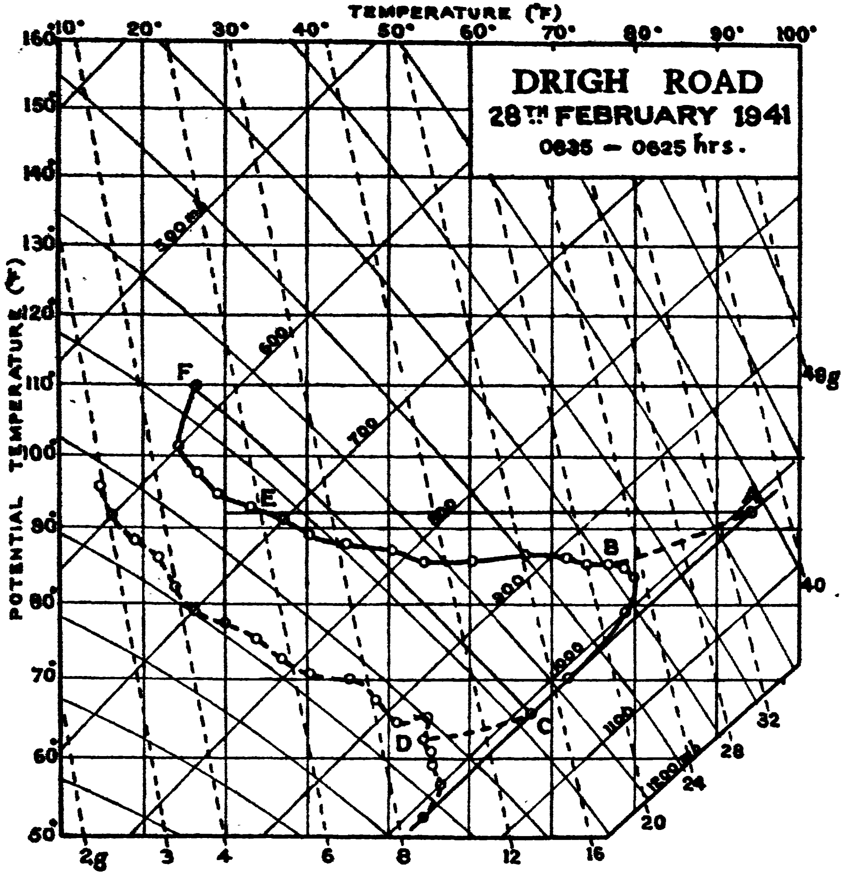
TEMPERATURE (°F)
10° 20° 30° 40° 50° 60° 70° 80° 90° 100°
DRIGH ROAD
28TH FEBRUARY 1941
0635 – 0625 hrs.
POTENTIAL TEMPERATURE (°F)
160 150 140 130 120 110 100 90 80 70 60 50
300 mb
600
700
800
900
1000
1100
1200 mb
A
B
C
D
E
F
2g 3 4 6 8 12 16 20 24 28 32 40 48g

Fig. 1.

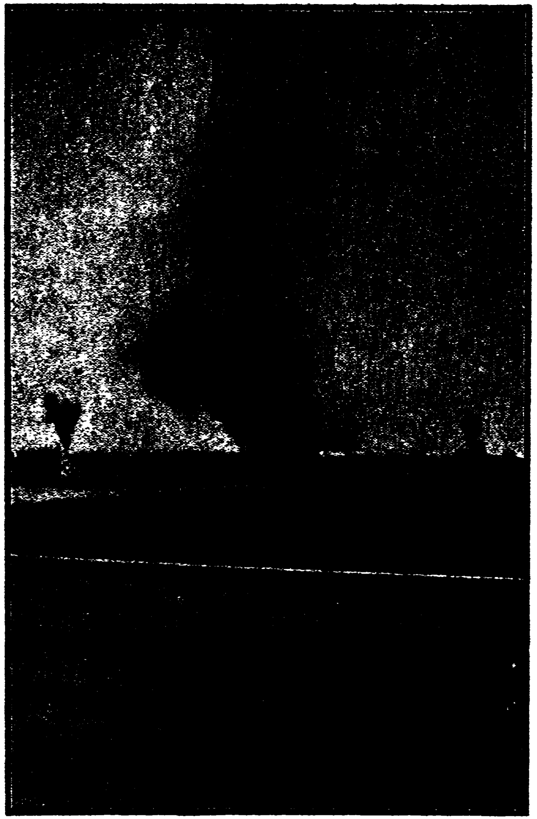

Fig. 2.

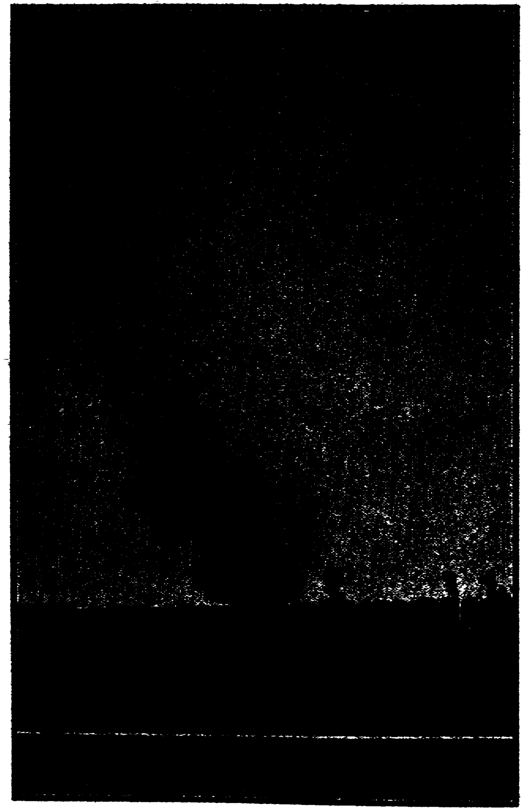

Fig. 3.

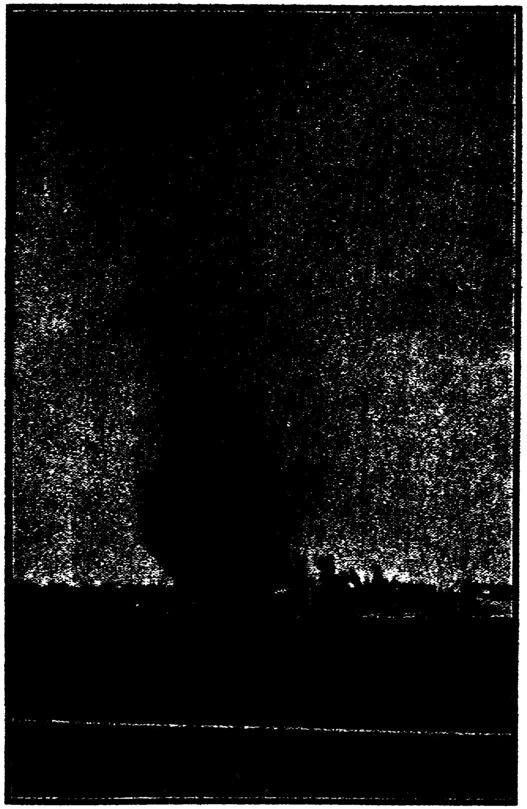

Fig. 4.

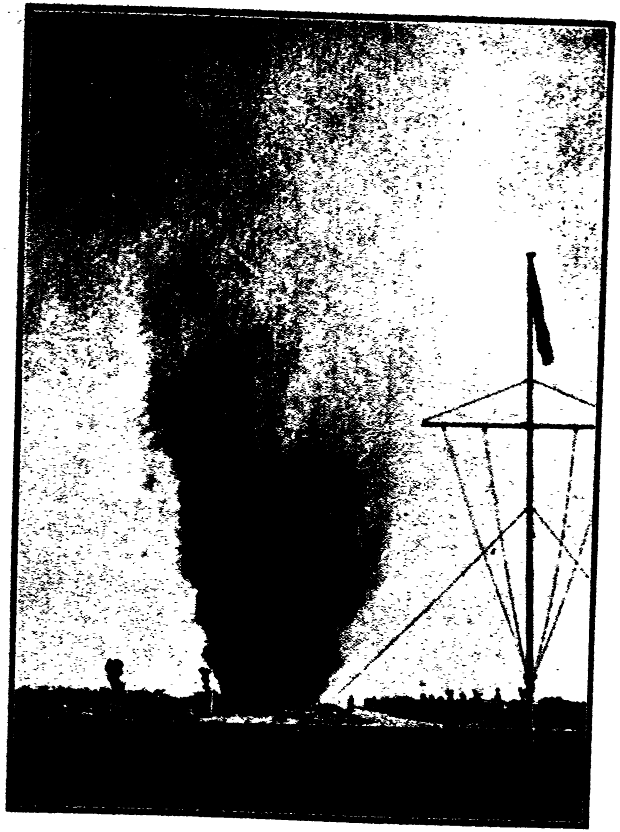

Fig. 5.

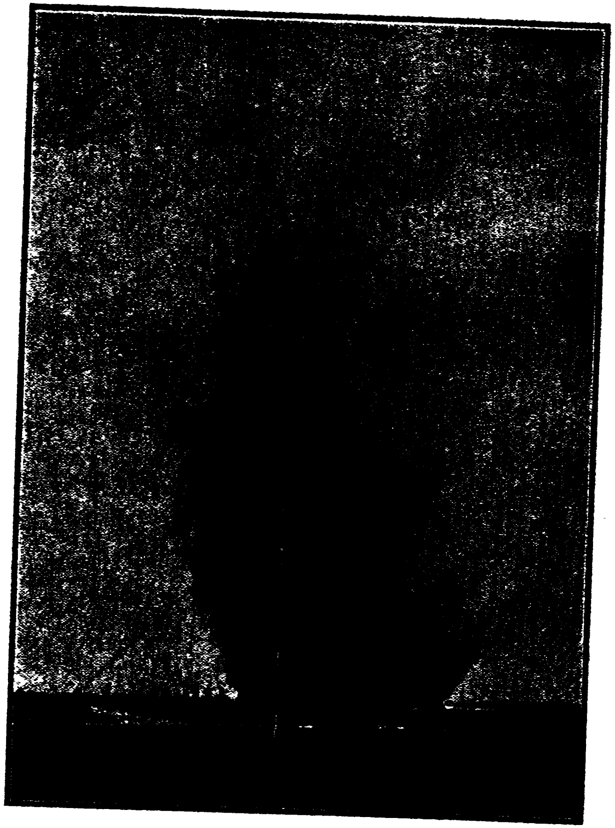

Fig. 6.

I.M.D.-Sc.N.100.

Plate IV

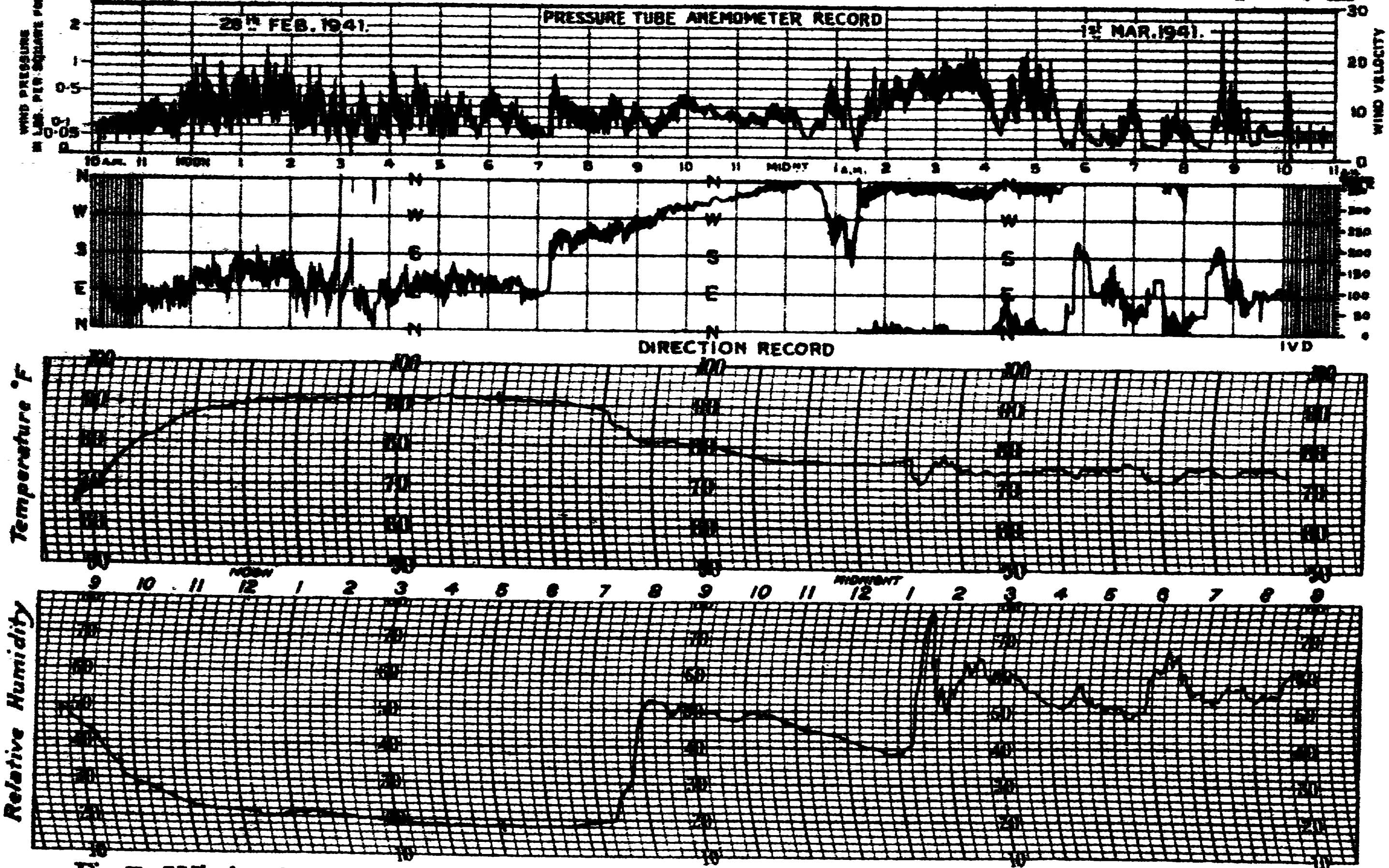

Fig. 7. Wind, Temperature and Relative Humidity at Drigh Road on 28th. Feb.—1st. Mar. 1941.

G.P.Z.P. Poona, 1942.

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